Fall 11-2012

COST-EFFECTIVE TREATMENT OF EXISTING GUARDRAIL SYSTEMS

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Civil Engineering

Under the Supervision of Professor Dean L. Sicking

Lincoln, Nebraska

November, 2012

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University of Nebraska, 2012

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A cost-effective means for upgrading existing barrier systems, which have deviations from standard practice (i.e., low-rail heights, antiquated end treatments, and improper installation) does not exist. As a result these systems remain on U.S. highways. Barrier systems with deviations from current practice may not perform as intended, thus resulting in fatalities and serious injuries from impacts with these safety devices. It is not plausible to eliminate fatalities and serious injuries from all guardrail impacts; but these numbers could be significantly reduced with the proper design, testing, installation, and maintenance of guardrail systems.

This report offers recommendations for upgrading W-beam guardrails based on benefit-to-cost analyses using the Roadside Safety Analysis Program (RSAP). This analyses was developed to simulate the most frequent and possible scenarios of existing W-beam barrier systems with deviations from standard practice. Before the analysis could be run, the field conditions and deviations from standard practice needed to be recognized and determined from a field investigation.

A field investigation was conducted on rural arterial highways in the state of Kansas to determine the nature of existing barrier systems with deviations from standard practice. For the study, the most prominent barrier was the strong-post, W-beam guardrail. The major deviations of the existing W-beam were low top-rail mounting-

height and antiquated end treatments (i.e. turned-down and blunt-end terminals). The W-beam guardrail with low rail heights and turned-down and blunt-end terminals were the focus of the RSAP analysis.

The varying guardrail heights were modeled in RSAP by changing the level of containment of the W-beam guardrail, and the antiquated end treatments were predefined features. The roadway and roadside features including hazards (culverts and slopes) were modeled after those found in the field investigation. Finally, cost-effective safety treatments were recommended for existing W-beam guardrail with low rail height and turned-down or blunt-end terminals which shielded culverts and slopes.

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1 INTRODUCTION

1.1 Background

The primary function of a guardrail is to prevent errant vehicles from impacting a roadside hazard or encroaching into a hazardous area. Guardrails are intended to shield a more severe hazard (based on judgment), yet many fatalities and serious injuries have resulted from vehicles impacting these safety devices. In fact, guardrail impacts resulted in approximately 1,000 fatalities and 28,000 injuries in the U.S. in 2010 [1]. Many severe and fatal crashes may be caused by outdated guardrail installations that did not satisfy the prior and/or current safety performance standards, including those established in the *Manual for Assessing Safety Hardware* (MASH) [2] or the *National Cooperative Highway Research Program* (NCHRP) Report No. 350 [3], which is still accepted by the Federal Highway Administration (FHWA) [4]. Existing guardrail installations can be found to be substandard in many ways, such as non-standard barrier types, antiquated end treatments, low rail heights, improper installations, variable post spacing, and inadequate lengths of need. It is not plausible to eliminate fatalities and serious injuries from all types of guardrail impacts; but these numbers could be significantly reduced with the proper design, testing, installation, and maintenance of current guardrail technologies.

In the early 1960s, roadside safety was not given the consideration deemed necessary to develop "forgiving roadside safety devices" [5]. Barriers were used to keep motorists from running off of the road or into roadside hazards, such as culverts and critical slopes. Little attention was given to the crash severity of the barrier itself. This process led to several potential inadequacies in terms of barrier configurations, such as blunt-end guardrail terminals, concrete guardrail posts, low rail mounting heights, and other deviations from currently applied guardrail standards. Due to limited funds, many of these substandard systems still exist along highways and roadways today. These deviations from standard practices may present major safety concerns to government agencies as well as the motoring public, which need to be evaluated and addressed.

Ideally, all substandard barrier installations would be upgraded to satisfy current safety and design guidelines. However, available funding is often insufficient to meet this goal. Guardrail installation guidelines are based on the assumption that these barriers are usually installed during highway construction projects and therefore benefit from an economic standpoint that limits overall transportation and labor costs of construction crew at the site. For example, when a highway project requires reconfiguration of the roadside, incorporating additional grading to accommodate guardrail terminals is relatively inexpensive. As such, agencies may be encouraged to upgrade existing substandard guardrail systems when a roadway undergoes a 3R project (resurfacing, rehabilitation, or restoration of the roadway) or when the guardrail undergoes extensive damage. It is necessary to determine when an existing guardrail installation is in need of a cost-effective upgrade even if the roadway is not under a 3R project. This type of guidance must be founded upon an economic analysis of a guardrail improvement, which includes accident, construction, maintenance, and repair costs for all options being evaluated.

Although it is recommended to have the most current and best available safety hardware on our nation’s highways and roadways, existing substandard barriers may still provide substantial benefit to the motorist population [6]. These existing barriers still provide some level of vehicle containment and are much cheaper for highway agencies to maintain relative to replacing them with new guardrail systems. However, at some point the accident costs associated with substandard guardrail will exceed the cost of installing a new improved barrier system. Therefore, a need exists to develop guidelines for determining when it is cost-effective to allow an existing guardrail system to remain in place, when it is necessary to remove the existing barrier system, or when the existing barrier system should be replaced with an updated or upgraded barrier system.

Guardrail installation guidelines are configured to provide the safest practical design for errant vehicles. Unfortunately, many components are relatively conservative. For example, guardrail length guidelines provided in the American Association of State Highway and Transportation Officials (AASHTO) *Roadside Design Guide* (RDG) [7] are based on vehicle runout distances traveled along the medians of divided highways observed from a 1960's investigation [9]. Another study of encroachments in Canada indicated that encroachment lengths measured in a 1970's investigation greatly overstated the distance that vehicles traveled along the roadside, causing the current guidelines pertaining to guardrail length of need to be re-evaluated [10].

Many parameters associated with guardrail installation guidelines, including length, can significantly increase the cost of upgrading older installations. However, these parameters may not contribute much to the reduction of injuries and fatalities in ran-off-road crashes. For example, as a guardrail is extended, the additional number of crashes with the protected hazard decline, but vehicle accidents into the guardrail and installation cost associated with the additional length increases steadily. Hence, the length of the guardrail reaches a point of diminishing return as it is lengthened.

1.2 Research Objective

The primary research objective of this study was to develop guidelines for determining when it is cost-effective to upgrade existing substandard guardrail installations with the use of a benefit-to-cost (B/C) analysis.

1.3 Research Scope

The research objective was achieved by performing several tasks. First, a field investigation was conducted to find guardrail systems located on two-way, two-lane highways in several states. This step included detailed descriptions and geometries of substandard barriers along with roadway geometries and roadside conditions. Next, a detailed data review was performed on the information obtained from the field investigation in order to better understand how existing guardrail systems deviate from current barrier standards. Then, a sensitivity analysis and engineering judgment were used to determine what types of barrier systems, roadway features, and hazards were to be evaluated. Subsequently, these parameters were investigated and evaluated within a set of detailed scenarios, which formed the basis of a B/C analysis utilizing the Roadside Safety Analysis Program (RSAP) [11]. Next, the results from the RSAP runs were tabulated to identify when existing barrier systems were satisfactory, needed to be removed, or needed to be upgraded. Finally, guidelines, conclusions, and recommendations were prepared regarding the cost-effective upgrade of existing guardrail systems based on the results obtained from the benefit-to-cost analysis.

2 LITERATURE REVIEW

2.1 Federal Policies

Numerous FHWA memorandums and technical advisories have been issued to assist with guidelines on repairing, replacing, or upgrading existing barrier systems. One such document states that if safety improvements beyond restoration are made to an existing barrier, the entire system should be brought up to current standards [12]. As such, changes and alterations to an existing barrier system cannot be implemented on a piece-by-piece basis. For example, it arguably may be considered negligent to install a current crashworthy guardrail end terminal on the end of an existing substandard guardrail system. Often, the upgrade of an existing barrier can only be accommodated with the removal of the entire system as well as the subsequent installation of a new system that conforms to current design practices and meets impact safety standards. Due to the moderate amount of outdated and/or substandard barriers along highways and roadways, it is not always a feasible option for state departments of transportation (DOTs) to completely remove and replace existing, substandard roadside barriers. As a result, many guardrail systems remain in place for many years with identifiable deviations from standard design practice.

The design of guardrail end treatments have drastically changed and improved over the last 50 years. In early installations, guardrail ends were terminated with either a blunt-end or a small spoon (i.e., fish-tale attachment), the latter of which was intended to eliminate the exposed leading edge of the W-beam rail. However, both designs allowed W-beam rail to impale and cut through vehicles during end-on impacts. This behavior initiated the development of the turned-down end terminal [13]. Turned-down ends were used to slope the guardrail to the ground in order to eliminate the risk of spearing an impacting vehicle. However, these ramped ends ultimately allowed a vehicle to climb the rail and become airborne, often resulting in vehicle rollover or heavy contact into the shielded hazard. These types of treatments have proven to be hazards themselves. As of 1990 and according to an FHWA memorandum, all turned-down terminals were no longer to be utilized on new installations and were to be replaced on existing barrier systems during safety improvement, hazard elimination, or 3R projects on high-speed, high-volume facilities [14]. In 1993, the FHWA issued a technical advisory which prohibited the use of turned-down, W-beam guardrail end terminals within the designated clear zone on defined roads with operating speeds of 50 mph (80 km/h) and above and with traffic volumes in excess of 6,000 vehicles per day (vpd) [15]. However, it was noted that turned-down end terminals may remain appropriate for use on the downstream ends of the barrier on divided highways and in locations where end-on, high-speed accidents are unlikely. In 1994, the FHWA required that state agencies provide due care in not allowing inappropriate guardrail end terminals to remain indefinitely on the National Highway System (NHS) [16]. This guidance included a replacement strategy for blunt-end and turned-down terminals [17].

Transitions, which join together two barriers with differing stiffnesses, strengths, and geometries by gradually increasing or decreasing the lateral stiffness, are another category of barrier systems which may include outdated features. When correctly designed, transitions redirect errant vehicles and prevent pocketing or snagging as a vehicle approaches the stiffer barrier from the direction of a less stiff barrier. Most existing substandard transitions are found near the connection region between guardrail systems and rigid bridge rails. However, W-beam guardrail systems may have been connected directly to a bridge rail without the use of additional posts or rail elements, adequate blockouts, or a rubrail. In these scenarios, the stiffness transition could very likely be considered unsatisfactory due to the significant potential for vehicle snag or pocketing near the bridge end. Consideration should be given to replacing or upgrading these existing transitions as the opportunity becomes available [18].

Existing W-beam barriers may also deviate from the current practice in terms of a substandard guardrail height. Low guardrail height can result from poor installation, settling posts, roadway overlays, and use of outdated guardrail designs. Substandard guardrail heights can affect the ability of a barrier to contain and redirect an errant vehicle. For example, the change in vehicle fleet from large passenger sedans to taller, heavier pickup trucks, vans, and sport utility vehicles has caused the old standard 27-in. (686-mm) guardrail to fail NCHRP Report No. 350 Test Level 3 (TL-3) safety performance criteria [19]. Because of this result, FHWA issued a memo which required all newly-installed W-beam guardrail heights to be at least 27¾ in. (705 mm) to the top of the rail, and transportation agencies are recommended to adopt a 31-in. (787 mm) high guardrail system for all new installations. MASH testing has also shown some performance issues with 27¾-in. (705-mm) high guardrail designs, and the FHWA recommendation was the result of several testing programs which demonstrated improved crash-test performance at the 31-in. (787-mm) height [19].

2.2 Development of Barrier Standards

Prior to implementation, new roadside safety hardware is evaluated through the use of full-scale crash testing according to current impact safety guidelines and procedures. The full-scale crash tests allow designers to observe and evaluate the performance of the safety features for the worse-practical impact conditions. Guardrail performance is evaluated according to several measures, such as structural adequacy, occupant risk, and vehicle trajectory. Prior to 1962, there were no standardized testing criteria for designing or evaluating roadside safety devices. Thus, it was difficult to evaluate the performance of newly designed barriers. Then, the *Proposed Full-Scale Testing Procedures for Guardrails (Circular 482)* was developed [20]. This one-page document was the first set of guidelines for testing and evaluating roadside barriers. It standardized all vehicle crash testing criteria. It specified parameters such as vehicle mass, impact speed, and approach angle of the crash tests. Guardrail systems developed after this date had to pass all test criteria presented in the report in order to be implemented on highways.

Since the inception of Circular 482, the roadway conditions have changed drastically. The vehicle fleet, average daily traffic (ADT), and highway design speeds have also changed, and the safety standards that are used to evaluate barrier technologies have evolved. Guardrail testing guidelines and procedures have added new and more thorough test criteria to increase the safety of the roadsides. After Circular 482 [20], there have been six testing procedures for evaluating longitudinal barriers: NCHRP Report No. 153 (1974) [21]; Circular 191 (1978) [22]; NCHRP Report No. 230 (1981) [23]; AASHTO *Guide Specifications for Bridge Railings* (1989) [24]; NCHRP Report No. 350 (1993) [3]; and MASH (2009) [2]. Each testing standard involved more detailed testing criteria than the previous published criteria. Most updates either demanded more test criterion or improved the methods for evaluating safety performance of hardware and/or features by including the level of roadway and vehicle type. The major changes to the full-scale crash test criteria are listed below.

Circular 482 (1962) [20]

- First document to standardize full-scale crash test criteria
- Four specifications on test article installation
- One vehicle size
- Six test conditions
- Three evaluation criteria

NCHRP Report No. 153 (1974) [21]

- First complete test matrix
- Specified parameters to be measured with methods and limits to meet
- Simple report writing formats included
- Added small car test vehicle
- Changed impact speed from 20 mph (32.2 km/h) to 60 mph (96.6 km/h)

Circular 191 (1978) [22]

- Standardize soil for post installation
- Test vehicles updated
- Evaluation criteria changed

NCHRP Report No. 230 (1981) [23]

- Added more test vehicles
- New testing procedures added to meet available technologies
- Evaluation criteria updated
- Test matrices updated
- Basic in-service evaluation of safety features added

AASHTO *Guide Specifications for Bridge Railings* (1989) [24]

- Document specified on the testing of bridge rails
- Added pickup truck, single-unit truck, and tractor-trailer test vehicles

NCHRP Report No. 350 (1993) [3]

- Six test levels (TL-#) for different roadway conditions
- Added compact car
- ¾-ton pickup truck replaced large passenger car
- Testing matrices for more roadside features (work zone devices)
- Additional and different testing conditions
- Added computer simulation evaluation procedures
- Conversion to SI units
- Guidelines for critical impact point selection
- Enhanced measurement techniques to occupant risk values
- Optional side impact testing criteria added

MASH (2009) [4, 2]

- Small car impact angle increased from 20 to 25 degrees

- Impact speed for single-unit truck test increased from 80 km/h to 90 km/h
- Impact angle for length-of-need test of terminals and crash cushions increased from 20 to 25 degrees
- Impact angle for oblique end-on impacts of gating terminals and crash cushions reduced from 15 to 5 degrees
- Impact point for small vehicle tests on cable barrier changed to the mid-span of posts to evaluate the potential for under ride, while the target impact point for all other test vehicles shall be limited to 1 ft (0.3 m) upstream of the post for all test conditions
- The barrier top mounting height is recommended to be set at the maximum for small car tests and at the minimum for pickup truck tests
- Performance-based specifications for soil are used in lieu of the material-based specifications to help ensure consistency in soil strength
- Cable tension is required to be set to the value recommended for 100 degrees Fahrenheit
- Minimum installation length requirements are more clearly specified
- The size and weight of test vehicles is increased to reflect the increase in vehicle fleet size:
    - the 820C test vehicle is replaced by the 1100C
    - the 2000P test vehicle is replaced by the 2270P
    - the single-unit truck mass is increased from 8,000 kg to 10,000 kg
    - the light truck test vehicle (2270P) must have a minimum center of gravity height of 28 in.
- The option for using passenger car test vehicles older than 6 years is removed
- Windshield and occupant compartment damage evaluation uses quantitative instead of qualitative criteria
- All evaluation criteria will be pass/fail, eliminating the “marginal pass”
- Reporting the exit box evaluation criterion is required
- Language emphasizing the importance of in-service evaluation is added
- All newly designed barriers must be tested under MASH

Current vehicles are much taller and heavier than vehicles of the past as large sport utility vehicles (SUVs) and pickup trucks have become popular in society [25]. Many existing guardrail systems installed on highways are not designed to contain these larger vehicles under current impact conditions, thus guardrail systems that met past testing standards (prior to NCHRP 350) may potentially be obsolete. Along with the change in vehicle fleet, the ever-growing traffic volumes also may affect the need for guardrail systems. Higher traffic volumes relate to higher frequencies of ran-off-road accidents. Additionally, higher posted speeds on highways can lead to more severe impacts with the safety barriers. These two factors require that new barrier installations be safer and more forgiving to errant vehicles and their motorists.

Full-scale vehicle crash testing is often used to evaluate the safety performance of a barrier system. However, some may argue that a barrier may also be evaluated through an in-service performance evaluation. An in-service performance evaluation provides a broad range of information on vehicle collision characteristics (e.g., number of accidents and the extent of injuries), environmental, operational, and maintenance situations for typical roadway conditions. NCHRP Report No. 490, *In-Service Performance of Traffic Barriers* [26], utilizes a step-by-step method of evaluating existing barrier systems. This report assists in determining if and how a roadside safety feature performs in actual field conditions as compared to crash test results. An in-service performance evaluation would also provide a check against the evaluation results obtained from full-scale testing by the laboratories.

In addition to the new-feature evaluation in NCHRP Report No. 490, MASH [2] has specified a continuous in-service monitoring method for barrier systems. After passing the brief new-feature, in-service performance evaluation (typically 3 years), a continuous monitoring system is used on a roadside safety feature to ensure the device continues to perform as designed with the changing roadway conditions. This process will provide a way to determine the effects of changing roadway variables, such as vehicle fleet, growing ADT, and roadway design speeds.

2.3 Barrier Guidelines

After roadside safety devices have been deemed acceptable by passing all pertinent crash test criteria, they can be used on current highways. There are many different barrier installation guidelines that layout which systems are acceptable for specific roadway conditions based on a successfully-tested impact level. These documents are described in the following sections.

2.3.1 2006 Roadside Design Guide (RDG)

The *Roadside Design Guide* (RDG) [7] was developed and published by the American Association of State Highway and Transportation Officials (AASHTO). The RDG was intended to assist highway agencies in developing cost-effective roadside safety standards, while focusing on safety treatments that can minimize the likelihood of serious injuries and fatalities when a motorist inadvertently leaves the roadway. Guardrails can pose increased risk to errant motorists themselves. As such, a guardrail system should only be implemented if the crash severity and risks are less than that provided by the hazard itself. This guide combines current research and practical experience to create guidelines based on the guardrail risk versus the hazard risk concept. The RDG also assists with the basic design of guardrail, including guardrail selection for particular performance or test levels, guardrail structural characteristic (e.g., deflection allowance), and guardrail placement (e.g., lateral offset, flare rate, and length of need). The Roadside Design Guide was updated in 2011 [8].

2.3.2 AASHTO Bridge Guide

The *AASHTO Load and Resistance Factor Design (LRFD) Bridge Design Specifications* [27] were developed for the design, evaluation, and rehabilitation of bridges and bridge features. These specifications employ the LRFD methodology developed from current statistical knowledge of loads and structural performance. Current bridge rail designs and installation practices are described in these specifications.

2.3.3 Highway Safety Design and Operations Guide (Yellow Book)

The *Highway Safety Design and Operations Guide* (Yellow Book) [28] was developed by AASHTO. This document discusses general highway safety and defines specific roadway design elements, such as design speed, horizontal and vertical alignments, and roadsides. The Yellow Book gives a basic guide of when to implement barrier systems on different highway functional classes.

2.3.4 A Guide to Standardized Highway Barrier Hardware (Hardware Guide)

Published jointly by AASHTO, the American Road and Transportation Builder's Association (ARTBA), and the Association of General Contractors (AGC), A *Guide to Standardize Highway Barrier Hardware,* or the Hardware Guide, contains drawings and specifications for barrier systems and their components [29]. Most systems in the Hardware Guide had been crash tested and accepted by NCHRP Report No. 350 or propr testing standards. This guide includes a sample of different barrier types but does not have a comprehensive list of all barriers. The barriers contained in the Hardware Guide include the most commonly-used barrier systems in the U.S. The Hardware Guide provides specifications and materials corresponding to the barrier elements described therein.

2.4 Crashworthy Barriers, Terminals, and Transitions

FHWA defines crashworthy devices as those that have passed all pertinent crash tests conducted under the procedures defined in NCHRP Report No. 350 or MASH. It is important to be familiar with crashworthy roadside safety systems and their components when evaluating any deviations of existing barriers. For this study, barriers conforming to the Test Level 3 (TL-3) impact safety standards were considered. In this section, common crashworthy longitudinal barriers will be examined in order to make later comparisons to existing barrier systems with deviations from current design practice.

2.4.1 Strong-Post W-Beam Guardrail

Current W-beam guardrail systems are considered to be either flexible or semi-rigid guardrail systems depending on the post size and spacing. The major components of a current standardized W-beam guardrail systems include a rolled steel rail sections in the shape of a “W”, steel or wooden posts, and with/without blockouts. The steel W-beam thickness ranges from 14 to 10 gauge (1.90 to 3.42 mm) with a typical thickness of 12 gauge (2.66 mm).

Steel post cross sections range between W6x8.5 to W6x12 (W152x13.4 to W152x17.9). Wood posts can utilize a circular or rectangular cross section. The circular cross sections of accepted W-beam guardrail systems have a diameter between 7 in. and 8 in. (178 mm and 203 mm). A typical post rectangular cross section is 6 in. x 8 in. (152 mm x 203 mm). Most W-beam guardrail systems, which meet current standards, utilize a blockout to help reduce vehicle snag on posts as well as to maintain rail height. These blockouts are either wooden or plastic with typical dimensions of 6 in. x 12 in. x 14¼ in. (152 mm x 305 mm x 362 mm) or 6 in. x 8 in. x 14¼ in. (152 mm x 203 mm x 362 mm).

Current standards require a minimum top-rail mounting height of 27¾ in. (705 mm), but it is recommended that newly installed barriers utilize a 31-in. (787-mm) top-rail height [19]. Lap splices typically use eight ⅝–in. (16-mm) diameter steel bolts to connect two spans of W-beam guardrail at a splice location. Typical post spacing for a strong-post W-beam guardrail system is 6 ft - 3 in. (1.9 m). Typically, all steel components are galvanized to prevent and/or reduce corrosion, thus extending the design life of the barrier.

The Midwest Guardrail System (MGS) is a non-proprietary, strong-post, W-beam guardrail [30]. On the MGS system, the splices are located between the posts, and the nominal rail height is set to 31 in. (787 mm). Originally, the MGS was cash tested, met all criteria set forth by NCHRP Report No. 350, and was accepted as a TL-3 longitudinal barrier [31]. The MGS was later accepted according to the MASH impact safety standards [32-33]. The MGS barrier is shown in Figure 1.

2.4.2 W-Beam Guardrail End Terminals

There are many different designs of W-beam guardrail end terminals which meet all current crash test standards. These terminals must provide anchorage to develop the full capacity of the guardrail and safely redirect or contain head-on impacts. Most terminals attached to W-beam guardrail are known as gating terminals, which when struck, will allow the vehicle to go behind and beyond the terminal end. W-beam end terminals can be tangent or flared. Tangent terminals denote that the end treatment is tangent to the roadway while the barrier is parallel to the roadway. Tangent terminals dissipate kinetic energy in head-on impacts and stop an impacting vehicle over a safe distance. Some flared terminals allow an impacting vehicle to travel much farther after

Figure 1. Midwest Guardrail System (MGS)

contact, but the flare angle minimizes head-on impacts. Most W-beam terminals utilize breakaway wooden and/or steel posts in order to be more forgiving during head-on impacts. Steel cables are often used to develop the necessary strength for a redirecting an impacting vehicle but will release during a head-on impact. An impact head is also used on most W-beam terminal types so that the rail cannot spear the impacting vehicle. There are many different types of currently-accepted W-beam terminal designs. All designs safely stop a vehicle during head-on impacts and provide adequate strength to redirect a vehicle during an impact near the terminal end.

An example of a W-beam terminal, which meets all current standards, is the Sequential Kinking Terminal (SKT). The SKT is a tangent, energy-absorbing terminal that is configured with 6 posts and can be connected to the MGS. The SKT met all criteria set forth by NCHRP Report No. 350 at TL-3 for a W-beam end terminal [34-35]. All posts are either wood (BCT or CRT) or steel breakaway posts. The length of the end terminal is 37.5 ft (11.4 m). The SKT impact head is used to extrude the W-beam rail after a head-on impact, dissipating the impact energy over a relatively long distance as the rail is deformed. Posts nos. 1 and 2 are BCT timber posts and are placed in steel foundation tubes. Post nos. 3 through 6 are CRT timber posts with wooden blockouts. Posts were spaced at 6 ft - 3 in. (1.9 m) on center with a soil embedment depth of 39 in. (991 mm). The SKT terminal is shown in Figure 2.

2.4.3 W-Beam-to-Concrete Bridge Rail Transition

Most approach guardrail transitions connect a semi-rigid, W-beam to a rigid concrete bridge rail. The major concern of transitioning from a W-beam guardrail to a concrete bridge rail is vehicle pocketing, where an errant vehicle deflects the semi-rigid

Figure 2. Sequential Kinking Terminal (SKT)

W-beam far enough that the vehicle impacts the end of the rigid bridge rail, posing significant risk to the motorist. To mitigate this, the W-beam is strengthened to become more rigid over a transition length. The particular stiffness of the W-beam guardrail is achieved by a combination of the following options: reducing post spacing; installing larger posts; mounting a thicker rail element (stacked or nested w-beam); adding a thrie beam rail element to the transition; and creating a strong connection between the W-beam to the bridge rail element. To reduce the likelihood of wheel snagging on the end of the parapet, some transitions utilize a rubrail or curb. An example of a guardrail-to-concrete barrier transition that meets all NCHRP Report No. 350 standards is shown in Figure 3 [36-37].

2.4.4 Cable Barriers

Cable barriers are flexible guardrail systems and are generally more forgiving than other guardrail systems because deflection occurs over a larger span when an errant vehicle strikes the system. Cable barriers require a larger working width due to this large dynamic deflection. These barriers redirect impacting vehicles when enough tension is developed in the cables. The posts are weak and are designed to hold the cable in position until the system is impacted, at which point, they are easily bent or broken. A typical post is an S3x5.7 (S76x8.5) steel section, but many-currently accepted cable barriers have a unique post design. Typical post spacing varies from 10 to 20 ft (3.0 to 6.1 m) center-to-center. Cable barriers utilize either three or four ¾-in. (19-mm) diameter, 3x7 galvanized wire ropes. Top cable heights range from 27 in. to 41½ in. (686 mm to 1,054 mm).

Cable barriers have been installed with either low tension or high tension. Low-tension barriers are only tensioned enough to reduce the sag of the cables between posts

Figure 3. W-beam-to-Bridge Rail Transition

during temperature fluctuations. The high-tension cables have been implemented to redirect an errant vehicle with less deflection and decreased maintenance. High-tension cable barriers are tensioned between 3 kips and 8 kips (13.4 kN and 35.6 kN). The cable-to-post connections for each system typically utilize a steel clip or rounded U-bolt. These connections are designed to release the cables from the posts to prevent development of localized stresses on the posts. The SAFENCE is an example of a high-tension, 3-cable median barrier [38]. This barrier system was successful under the MASH criteria [39], and is shown in Figure 4.

2.4.5 Cable Guardrail End Terminal

Currently-accepted cable end terminals are similar to W-beam terminals because they are designed to develop the full capacity of the guardrail and safely contain a head-on impact. The cable end terminal section is typically anchored to the ground or to multiple end posts to develop enough strength to redirect oblique impacts downstream from the end system. Many of the currently accepted cable terminal designs have incorporated a cable release on the anchor. Similar to the W-beam terminals, these systems have both flared and tangent designs. In many of the systems, the posts near the ends are breakaway to be more forgiving to errant vehicles. An example of a breakaway end treatment is the MwRSF cable end terminal [40]. This system was successful under the NCHRP Report No. 350 criteria [41] and is shown in which is shown in Figure 5.

Figure 4. Safence Three-Cable High-Tension Barrier

Figure 5. MwRSF Cable End Terminal

2.5 W-Beam with Deviations from Standard Practice Studies

2.5.1 Rail Height Effects

There was a study performed on the G4(1S) W-beam guardrail system at varying rail top mounting heights to investigate the effect of different rail heights from the standard 27¾ in. (705 mm) top-rail height [25]. This study utilized both full-scale crash testing and finite element simulation to evaluate the safety performance of W-beam guardrail at varying rail heights. Crashes were investigated with a 2000P pickup truck impacting the W-beam guardrail at 62.1 mph (100 km/h) and 25 degrees (NCHRP Report No. 350 test designation 3-11). Simulations were performed on top-rail heights of 24⅝ in. (625 mm), 26⅛ in. (664 mm), 27¾ (705 mm), 29⅛ (740 mm), and 30⅝ (778 mm). The results from the study showed that lower rail heights of 24⅝ in. (625 mm) and 26⅛ in. (664 mm) had increased the potential for vehicle override of the W-beam guardrail system, while the 27¾ (705 mm), 29⅛ (740 mm), and 30⅝ (778 mm) redirected the vehicle. Then, two full-scale crash tests were performed on a W-beam guardrail with a 25 in. (635 mm) and 27¾ (705 mm) to validate the simulation results. The pickup truck redirected during the 27¾ (705 mm), but the 25 in. (635 mm) resulted in pickup truck override of the barrier. Simulation and full-scale crash test results showed a high risk of vehicle override when the W-beam guardrail is lower than the standard height.

Another study of the Midwest Guardrail System (MGS) at higher top-rail mounting heights was also conducted to investigate barrier performance at heights greater than the recommended 31-in. (787-mm) top-rail mounting height [42]. The MGS systems were evaluated with 34-in. (864-mm) and 36-in. (864-mm) top-rail mounting heights. Both system heights were found to satisfy MASH TL-3 evaluation criteria for test no. 3-

10. This study showed little effect of a higher top-rail mounting height under 1100C impact events within the length of need.

2.5.2 W-Beam Barrier Damage

FHWA's *W-Beam Guardrail Repair - A Guide for Highway and Street Maintenance Personnel* informs highway officials when to repair damaged guardrail [43]. Various guardrail conditions were categorized as: (1) guardrail no longer reasonably functional; (2) guardrail should function adequately under a majority of impacts; and (3) should not impair the guardrail's ability to perform. These functional categories come from the conditions rail element, posts, deflection (amount out of alignment), and top-rail height. Two major conclusions from this report were when the top-rail height was found to be less than or equal to 24 in. (610 mm) or the W-beam guardrail was missing 3 or more posts, the guardrail was deemed as no longer reasonably functional. This guide also included when it is pertinent to repair many W-beam guardrail features, such as bridge rail transitions and end terminals.

Criteria for Restoration of Longitudinal Barriers was another report which provides guidance in identifying levels of damage to W-beam guardrail barriers [44]. This study evaluated commonly found barrier damage utilizing pendulum testing, full-scale crash testing, and finite element simulations. The study evaluated W-beam barrier damage such as rail tear, missing splice bolts, twisted/missing blockouts, hole in rail, post deflection, missing/broken posts, post separation from rail, and rail flattening. When evaluating each damage type, the study ranked them as low, medium, and high priority to repair. This guide also included generic end terminal guidance.

2.6 Prior Benefit-to-Costs Studies

2.6.1 Roadside Grading Guidance

Roadside Grading Guidance Phase I and II [45-46] were developed to create a

2.6.2 Low-Volume Roads

Cost-Effective Safety Treatments for Low-Volume Roads was a study was a study performed to evaluate common hazards on low volume roads [47]. In this study a field investigation was done in the states of Nebraska and Kansas to determine the nature of roadside hazards on low-volume roadways. Hazards documented in the field study included culverts, trees, slopes, ditches, and bridges. This project utilized the RSAP program to determine the most cost-effective safety treatment option for each hazard.

2.6.3 Culverts

Danel [48]

2.7 W-beam Containment Level at Varying Top Guardrail Mounting Height

3 FIELD INVESTIGATION OF EXISTING BARRIER SYSTEMS

3.1 Overview

For this study, it was necessary to gain a better understanding of the current state of existing barrier systems with known deviations from standard practice. Thus, an extensive site survey was conducted in order to document many of these barrier systems found along rural arterial highways in Kansas. All system geometries, components, deviations from standard barriers, shielded hazards, and the roadway conditions were documented during the survey using the field investigation data sheet shown in Appendix A. Each field site and barrier installation was also thoroughly photographed to aid in the subsequent analysis. The field investigation took place during the summer of 2009. Highway sites within the state of Kansas were suggested by DOT personnel and selected by MwRSF staff for this investigation. The field investigation team made an effort to visit numerous sites to obtain a wide variety of barrier types, roadway conditions and classifications, and geographical areas during the survey period. It should be noted that if a barrier system and hazard type were nearly identical for multiple locations, then only a few similar sites were documented; since, information pertaining to different barrier systems or deviations from standard barriers was deemed more valuable than redundant documentation of known issues.

The types of barrier systems that were documented in the field investigation were: (1) strong-post, W-beam guardrails; (2) cable guardrails; (3) concrete barriers; (4) channel rails; and (5) modified versions of W-beam barrier systems. These barrier systems varied in length, height, hazard shielded, roadway offset, and condition pertaining to aged components, prior impacts, and installation practices. These real-world barrier systems are described in greater detail later in this chapter.

The highway functional classes of the roadways that were documented in the study included minor arterial, major collector, and other principal arterial, two-lane roadways without medians, as defined by Kansas DOT. Out of the 68 barriers investigated, 61 were found on minor arterial roadways. There were only 7 roadways that were documented as major collector roadways. The lane width of these highways varied from 9 to 12 ft (2.7 to 3.7 m), while the vast majority had a 12-ft (3.7-m) lane width. The shoulder width ranged from 0 to 12 ft (0 to 3.7 m), and the posted speed limit ranged between 35 and 65 mph (56.3 and 104.6 km/h), although most locations had a 65-mph (104.6-km/h) posted speed limit. The ADT on the Kansas roadways documented in the field investigation ranged from 300 to 11,000 vpd, as determined by traffic volume maps.

The barrier systems were found to shield various fixed objects or geometric features, such as culvert openings, roadside slopes, bridge rail ends, small waterways, and trees, which can be hazardous to errant motorists and vehicles. However, the most common shielded fixed objects were culvert openings and roadside slopes. A summary of all documented systems is shown in Table 1.

All concrete box culverts included wingwalls. In the field investigation, culvert lengths varied between 6 ft and 50 ft (1.8 m and 15.2 m). The width of the culverts ranged between 5 ft and 30 ft (1.5 m and 9.1 m). The drop height of the culverts ranged between 3 ft and 14 ft (0.9 m and 4.3 m). The lateral offsets of culverts varied between 0 ft and 6 ft - 6 in. (0 m and 2.0 m) away from the roadway edge. A summary of culvert

Table 1. Summary of Field Investigation – Barrier, Hazard, and Site Conditions

System No.	Barrier System Description	Hazard Type	Lane Width		Shoulder Width		Speed Limit		Curve
			(ft)	(m)	(ft)	(m)	(mph)	(km/h)	
1	Strong-Post, W-Beam	bridge rail end	12	3.7	2	0.6	65	104.6	none
2	Strong-Post, W-Beam	bridge rail end	11	3.4	1	0.3	65	104.6	none
3	Strong-Post, W-Beam	bridge rail end	11	3.4	1	0.3	65	104.6	none
4	Strong-Post, W-Beam	bridge rail end	11	3.4	0.67	0.2	65	104.6	none
5	Strong-Post, W-Beam	bridge rail end	11	3.4	2	0.6	65	104.6	none
6	Strong-Post, W-Beam	bridge rail end	11	3.4	0	0.0	65	104.6	none
7	Strong-Post, W-Beam	bridge rail end	NA	NA	NA	NA	NA	NA	none
8	Strong-Post, W-Beam	bridge rail end	12	3.7	12	3.7	65	104.6	none
9	Strong-Post, W-Beam	bridge rail end	11	3.4	1	0.3	60	96.6	none
10	Strong-Post, W-Beam	culvert opening	12	3.7	3	0.9	65	104.6	none
11	Strong-Post, W-Beam	culvert opening	12	3.7	1	0.3	65	104.6	none
12	Strong-Post, W-Beam	culvert opening	9	2.7	3	0.9	55	88.5	yes
13	Strong-Post, W-Beam	culvert opening	9	2.7	3	0.9	55	88.5	yes
14	Strong-Post, W-Beam	culvert opening	9	2.7	2	0.6	55	88.5	yes
15	Strong-Post, W-Beam	culvert opening	12	3.7	2	0.6	65	104.6	yes
16	Strong-Post, W-Beam	culvert opening	12	3.7	NA	NA	65	104.6	none
17	Strong-Post, W-Beam	culvert opening	11	3.4	8	2.4	65	104.6	none
18	Strong-Post, W-Beam	culvert opening	11	3.4	4	1.2	65	104.6	none
19	Strong-Post, W-Beam	culvert opening	12	3.7	4	1.2	65	104.6	yes
20	Strong-Post, W-Beam	culvert opening	12	3.7	3	0.9	65	104.6	none

NA – Unable to document due to roadway conditions and/or other circumstances

Table 1. Summary of Field Investigation – Barrier, Hazard, and Site Conditions (Continued)

System No.	System Description	Hazard Type	Lane Width		Shoulder Width		Speed Limit		Curve
			(ft)	(m)	(ft)	(m)	(mph)	(km/h)	
21	Strong-Post, W-Beam	culvert opening	11	3.4	3.5	1.1	65	104.6	none
22	Strong-Post, W-Beam	culvert opening	NA	NA	NA	NA	NA	NA	none
23	Strong-Post, W-Beam	culvert opening	12	3.7	3	0.9	65	104.6	none
24	Strong-Post, W-Beam	culvert opening	12	3.7	2.67	0.8	65	104.6	none
25	Strong-Post, W-Beam	culvert opening	11	3.4	2	0.6	65	104.6	none
26	Strong-Post, W-Beam	culvert opening	12	3.7	2	0.6	65	104.6	none
27	Strong-Post, W-Beam	culvert opening	11	3.4	2	0.6	65	104.6	none
28	Strong-Post, W-Beam	culvert opening	12	3.7	2	0.6	55	88.5	none
29	Strong-Post, W-Beam	culvert opening	12	3.7	2.5	0.8	65	104.6	none
30	Strong/Concrete Post, W-beam	culvert opening	12	3.7	3	0.9	65	104.6	none
31	Strong/Concrete Post, W-beam	culvert opening	11	3.4	0.67	0.2	65	104.6	none
32	Strong/Concrete Post, W-beam	culvert opening	12	3.7	2.5	0.8	65	104.6	yes
33	Strong/Concrete Post, W-beam	culvert opening	12	3.7	2.5	0.8	65	104.6	none
34	Strong-Post, W-Beam	roadside slope	11	3.4	6	1.8	35	56.3	none
35	Strong-Post, W-Beam	roadside slope	12	3.7	1	0.3	45	72.4	none
36	Strong-Post, W-Beam	roadside slope	9	2.7	3	0.9	55	88.5	none
37	Strong-Post, W-Beam	roadside slope	11	3.4	4	1.2	55	88.5	none
38	Strong-Post, W-Beam	roadside slope	12	3.7	2	0.6	45	72.4	none
39	Strong-Post, W-Beam	roadside slope	11	3.4	1	0.3	55	88.5	yes
40	Strong-Post, W-Beam	roadside slope	11	3.4	1	0.3	65	104.6	none

NA – Not able to document due to roadway conditions and/or other circumstances

Table 1. Summary of Field Investigation – Barrier, Hazard, and Site Conditions (Continued)

System No.	System Description	Hazard Type	Lane Width		Shoulder Width		Speed Limit		Curve
			(ft)	(m)	(ft)	(m)	(mph)	(km/h)	
41	Strong-Post, W-Beam	roadside slope	12	3.7	2	0.6	50	80.5	none
42	Strong-Post, W-Beam	roadside slope	11	3.4	1	0.3	65	104.6	none
43	Strong-Post, W-Beam	roadside slope	11	3.4	0	0.0	65	104.6	none
44	Strong-Post, W-Beam	roadside slope	12	3.7	0.25	0.1	65	104.6	none
45	Strong-Post, W-Beam	roadside slope	12	3.7	3	0.9	60	96.6	none
46	2-Cable Low Tension	culvert opening	12	3.7	2.5	0.8	65	104.6	none
47	2-Cable Low Tension	roadside slope	12	3.7	4	1.2	65	104.6	none
48	2-Cable Low Tension	roadside slope	11	3.4	1	0.3	65	104.6	yes
49	2-Cable Low Tension	roadside slope	12	3.7	2	0.6	65	104.6	none
50	2-Cable Low Tension	roadside slope	12	3.7	3	0.9	65	104.6	none
51	2-Cable Low Tension	roadside slope	12	3.7	2.5	0.8	65	104.6	none
52	2-Cable Low Tension	roadside slope	12.5	3.8	8	2.4	55	88.5	yes
53	2-Cable Low Tension	roadside slope	11	3.4	0.5	0.2	65	104.6	none
54	1-Cable Low Tension	culvert opening	11	3.4	1	0.3	45	72.4	none
55	Strong-Post, Modified W-Beam	culvert opening	10	3.0	1	0.3	65	104.6	none
56	Strong-Post, Modified W-Beam	culvert opening	12	3.7	3.5	1.1	65	104.6	none
57	Strong-Post, Modified W-Beam	culvert opening	11	3.4	1	0.3	65	104.6	none
58	Strong-Post, Modified W-Beam	culvert opening	11	3.4	0.5	0.2	55	88.5	none
59	Strong-Post, Modified W-Beam	roadside slope	12	3.7	1	0.3	60	96.6	none
60	Strong-Post, Modified W-Beam	roadside slope	12	3.7	2	0.6	65	104.6	none

NA – Not able to document due to roadway conditions and/or other circumstances

Table 1. Summary of Field Investigation – Barrier, Hazard, and Site Conditions (Continued)

System No.	System Description	Hazard Type	Lane Width		Shoulder Width		Speed Limit		Curve
			(ft)	(m)	(ft)	(m)	(mph)	(km/h)	
61	Strong-Post, Modified W-Beam	roadside slope	12	3.7	1	0.3	65	104.6	none
62	Strong-Post, Modified W-Beam	roadside slope	12	3.7	0.5	0.2	65	104.6	none
63	Strong-Post, Modified W-Beam	roadside slope	11	3.4	6	1.8	65	104.6	none
64	Strong-Post, Channel Rail	roadside slope	12	3.7	0.5	0.2	40	64.4	yes
65	Strong-Post – Flat-Panel	roadside slope	11	3.4	6	1.8	65	104.6	none
66	Strong-Post – Flat-Panel	roadside slope	11	3.4	8	2.4	65	104.6	none
67	Strong-Post – Flat-Panel	roadside slope	11	3.4	6	1.8	65	104.6	none
68	Concrete Rail Installation	culvert opening	11	3.4	0.33	0.1	65	104.6	none

NA – Not able to document due to roadway conditions and/or other circumstances

geometries are shown in Table 2. Examples of the culvert systems found in the field investigations are shown in Figure 6.

The roadside slopes that were documented in the field investigation varied in length, width, slope rate, drop height, and lateral offset away from the roadway. The length of the slope varied between 30 ft and 10,560 ft (9.1 m and 3,219 m). All slopes had a width greater than 30 ft (9.1 ft). The cross slope over the length of the W-beam guardrail systems generally ranged between 5:1 and 1.5:1. The overall drop height of the slope varied between 7 ft and 15 ft (2 m and 4.6 m). The lateral offset from the face of the W-beam guardrail system to the slope break point ranged from 0 ft to 5 ft (0 m to 1.5 m). The cross slopes documented at existing W-beam guardrail systems are shown in Table 3. Examples of the documented roadside slopes are shown in Figure 7.

As previously noted, bridge rail ends were also documented in the field investigation. Bridge rail ends are typically placed at low lateral offsets away from the roadway edge, thus creating concern if not shielded or transitioned correctly.

For one particular site, a barrier system was used to shield both roadside trees and a small pond. Lateral tree offsets from the back of the rail of the W-beam guardrail system ranged from 5 ft to 15 ft (1.5 m to 4.6 m). The pond was laterally offset 5 ft (1.5 m) away from the back of the rail of the W-beam guardrail system. The trees and pond are shown in Figure 8.

Table 2. Summary of Existing Culvert Details

Culvert Site	Width		Length		Lateral Offset		Drop Height	
	(ft)	(m)	(ft)	(m)	(in.)	(mm)	(ft)	(m)
10	10	3.0	45	13.7	0	0	12	3.7
11	11	3.4	25	7.6	0	0	NA	NA
12	10	3.0	6	1.8	0	0	8	2.4
13	6	1.8	6.5	2.0	0	0	14	4.3
14	5	1.5	6.5	2.0	72	1829	NA	NA
15	8	2.4	21	6.4	10	254	NA	NA
16	10	3.0	25	7.6	12	305	NA	NA
17	30	9.1	25	7.6	22	559	NA	NA
18	30	9.1	20	6.1	12	305	NA	NA
19	30	9.1	6	1.8	76	1930	6	1.8
20	30	9.1	32	9.8	6	152	4	1.2
21	NA	NA	21	6.4	14	356	3	0.9
22	NA	NA	NA	NA	NA	NA	NA	NA
23	30	9.1	30	9.1	6	152	14	4.3
24	30	9.1	11	3.4	6	152	8	2.4
25	NA	NA	30	9.1	78	1981	NA	NA
26	NA	NA	25	7.6	12	305	NA	NA
27	30	9.1	30	9.1	6	152	NA	NA
28	30	9.1	12	3.7	0	0	NA	NA
29	30	9.1	25	7.6	NA	NA	NA	NA
30	20	6.1	25	7.6	0	0	14	4.3
31	NA	NA	NA	NA	NA	NA	NA	NA
32	NA	NA	25	7.6	6	152	NA	NA
33	NA	NA	25	7.6	6	152	NA	NA
46	12	3.7	18	5.5	0	0	NA	NA
54	26	7.9	10	3.0	0	0	NA	NA
55	30	9.1	7.5	2.3	0	0	NA	NA
56	8	2.4	22	6.7	0	0	NA	NA
57	NA	NA	30	9.1	12	305	NA	NA
58	NA	NA	13	4.0	56	1422	NA	NA
68	16	4.9	NA	NA	0	0	NA	NA

NA –Unable to document due to roadway conditions and/or other circumstances

Figure 6. Examples of Shielded Culvert Systems

Table 3. Summary of Existing Roadside Slope Details

Slope Site	Length		Drop Height		Lateral Offset		Cross Slope
	(ft)	(m)	(ft)	(m)	(ft)	(m)	X to Y
34	6,336	1931.2	NA	NA	3.5	1.1	2.5 to 1
35	100	30.5	6.5	2.0	0	0.0	2.5 to 1
36	NA	NA	11.5	3.5	NA	NA	NA
37	200	NA	NA	NA	0	0.0	2 to 1
38	876	267.0	12.5	3.8	2	0.6	2 to 1
39	500	152.4	NA	NA	3	0.9	2.5 to 1
40	639	194.8	12.5	3.8	0	0.0	NA
41	90	27.4	14	4.3	0	0.0	NA
42	404	123.1	13.5	4.1	5	1.5	2.5 to 1
43	300	91.4	NA	NA	0	0.0	4 to 1
44	400	121.9	12	3.7	0	0.0	NA
45	400	121.9	8	2.4	0	0.0	2.5 to 1
47	300	91.4	NA	NA	0	0.0	5 to 1
48	454	138.4	11	3.4	0	0.0	2.5 to 1
49	30	9.1	12.5	3.8	0	0.0	5 to 1
50	501	152.7	11	3.4	0.5	0.2	5 to 1
51	605	184.4	15	4.6	0	0.0	3 to 1
52	5,280	1609.3	11.5	3.5	0	0.0	NA
53	402	122.5	8	2.4	0	0.0	3.5 to 1
59	30	9.1	5.5	1.7	0	0.0	2.5 to 1
60	350	106.7	11	3.4	0	0.0	2.5 to 1
61	50	15.2	6	1.8	0	0.0	2.5 to 1
62	200	61.0	10.5	3.2	0	0.0	2 to 1
63	76	23.2	12.5	3.8	14	4.3	2.5 to 1
64	10,560	3218.7	21	6.4	4	1.2	3.5 to 1
65	64	19.5	11	3.4	4	1.2	3 to 1
66	64	19.5	7.5	2.3	4	1.2	3 to 1
67	273	83.2	13.5	4.1	5	1.5	3 to 1
Average	**890.3**	**279.8**	**11.2**	**3.4**	**1.6**	**0.5**	**3.0 to 1**
Max.	**10,560**	**3,219**	**21**	**6**	**14**	**4**	**5 to 1**
Min.	**30**	**9**	**6**	**2**	**0**	**0**	**2 to 1**

NA – Not able to document due to roadway conditions and/or other circumstances

Figure 7. Examples of Shielded Roadside Slopes

Figure 8. Examples of Shielded Trees and Pond

3.2 Strong-Post W-Beam Guardrail

3.2.1 General Configurations and Concerns

W-beam guardrails were the most common feature that was documented during the field investigation (45 of the 68 documented barrier systems). The W-beam guardrail systems utilized wood posts in 37 systems, steel posts in 4 systems, and concrete posts in 4 systems. Wooden posts were either round or rectangular sections with typical sizes of 7 in. (178 mm) diameter or 5½ in. x 7½ in. (140 mm x 191 mm), respectively. For the most part, the wooden posts were in good condition with some weathering and decay below the ground line. The steel and concrete posts had cross sections of W6x9 (W152x13.4) and 10 in. x 7 in. (254 mm x 178 mm), respectively. Nearly all of the systems utilized wooden blockouts. However, two guardrail systems utilized steel I-beam blockouts, and nine barrier systems did not use blockouts.

The W-beam rail sections were generally in good condition, with some systems containing early stages of corrosion (i.e., rust) and a few systems damaged due to prior impacts. The W-beam guardrail systems were anchored at the ends with various types of end terminals. Spoon (blunt-end) terminals were used on 40 of the W-beam guardrail systems, while the other five W-beam guardrail systems utilized turned-down end terminals. Most barriers systems utilized a splice with a 12½ in. (318 mm) lap and eight ⅝-in. (16 mm) diameter splice bolts. All splice locations were centered at post locations.

The barrier systems were offset away from the roadway edge by 1½ ft to 13 ft (0.5 m to 4.0 m) with a common offset of 6 ft (1.8 m). The W-beam barriers shielded culvert openings, roadside slopes, bridge rail ends, small waterways, and trees. A summary of the documented W-beam guardrail systems is shown in Table 4. Sample photographs of the existing W-beam guardrail systems are shown in Figures 9 through 12.

Table 4. Summary of Existing W-Beam Guardrail Systems – Barrier, Terminal, and Roadway Details

System No.	Post Material	Blockout Material	Terminal Type	Barrier Length (with Terminals)		Lateral Barrier Offset (roadway to barrier)		Post Spacing	
				(ft)	(m)	(in.)	(mm)	(in.)	(mm)
1	Wood	wood	spoon	255	77.7	NA	NA	75	1,905
2	Steel	none	spoon	NA	NA	NA	NA	NA	NA
3	Wood	wood	spoon	63	19.2	41	1,041	75	1,905
4	Wood	none	spoon	NA	NA	NA	NA	NA	NA
5	Wood	wood	spoon	89	27.1	NA	NA	75	1,905
6	Wood	wood	Turn-down	124	37.8	30	762	75	1,905
7	Wood	wood	spoon	NA	NA	NA	NA	NA	NA
8	Wood	wood	Turn-down	148	45.1	144	3,658	75	1,905
9	Wood	wood	spoon	50	15.2	50	1,270	75	1,905
10	Wood	wood	spoon	162.5	49.5	NA	NA	75	1,905
11	Wood	wood	spoon	125	38.1	NA	NA	75	1,905
12	Wood	wood	spoon	250	76.2	71	1,803	75	1,905
13	Wood	wood	spoon	162.5	49.5	74	1,880	75	1,905
14	Wood	wood	spoon	137.5	41.9	51	1,295	75	1,905
15	Steel	steel	spoon	200	61.0	NA	NA	75	1,905
16	Wood	wood	spoon	201	61.3	NA	NA	75	1,905
17	Wood	wood	spoon	180	54.9	48	1,219	150	3,810
18	Wood	wood	spoon	764	232.9	48	1,219	75	1,905
19	Wood	wood	Turn-down	150	45.7	126	3,200	75	1,905
20	Wood	wood	spoon	177	53.9	4	102	75	1,905
21	Wood	wood	spoon	177	53.9	NA	NA	75	1,905
22	Wood	wood	Turn-down	150	45.7	NA	NA	NA	NA
23	Wood	wood	spoon	128	39.0	99	2,515	75	1,905
24	Wood	wood	spoon	188	57.3	NA	NA	75	1,905

NA – Not able to document due to roadway conditions and/or other circumstances

Table 4. Summary of Existing W-Beam Guardrail Systems – Barrier, Terminal, and Roadway Details (continued)

System No.	Post Material	Blockout Material	Terminal Type	Barrier Length (with Terminals)		Lateral Barrier Offset (roadway to barrier)		Post Spacing	
				(ft)	(m)	(in.)	(mm)	(in.)	(mm)
25	Wood	wood	spoon	190	57.9	138	3,505	75	1,905
26	Wood	wood	spoon	210	64.0	96	2,438	75	1,905
27	Wood	wood	spoon	125.5	38.3	54	1,372	75	1,905
28	Wood	wood	spoon	151	46.0	53	1,346	150	3,810
29	Wood	none	spoon	477	145.4	104	2,642	150	3,810
30	concrete	none	spoon	25	7.6	119	3,023	75	1,905
31	concrete	none	spoon	NA	NA	NA	NA	NA	NA
32	wood/ concrete	none	spoon	132	40.2	118	2,997	75	1,905
33	wood/ concrete	none	spoon	138	42.1	118	2,997	75	1,905
34	steel	none	spoon	6336	1931.2	18	457	150	3,810
35	wood	wood	spoon	100	30.5	50	1,270	150	3,810
36	wood	wood	spoon	NA	NA	NA	NA	NA	NA
37	wood	none	spoon	200	61.0	63	1,600	150	3,810
38	steel	steel	spoon	896	273.1	68	1,727	75	1,905
39	wood	wood	spoon	501	152.7	65	1,651	75	1,905
40	wood	wood	spoon	739	225.2	56	1,422	75	1,905
41	wood	wood	spoon	155	47.2	63	1,600	75	1,905
42	wood	wood	spoon	90	27.4	NA	NA	75	1,905
43	wood	wood	spoon	503.5	153.5	104	2,642	75	1,905
44	wood	wood	spoon	400	121.9	49	1,245	75	1,905
45	wood	wood	spoon	551	167.9	52	1,321	75	1,905

NA – Not able to document due to roadway conditions and/or other circumstances

Figure 9. Examples of Existing W-Beam Guardrail Systems

Figure 10. Examples of Existing W-Beam Guardrail Systems

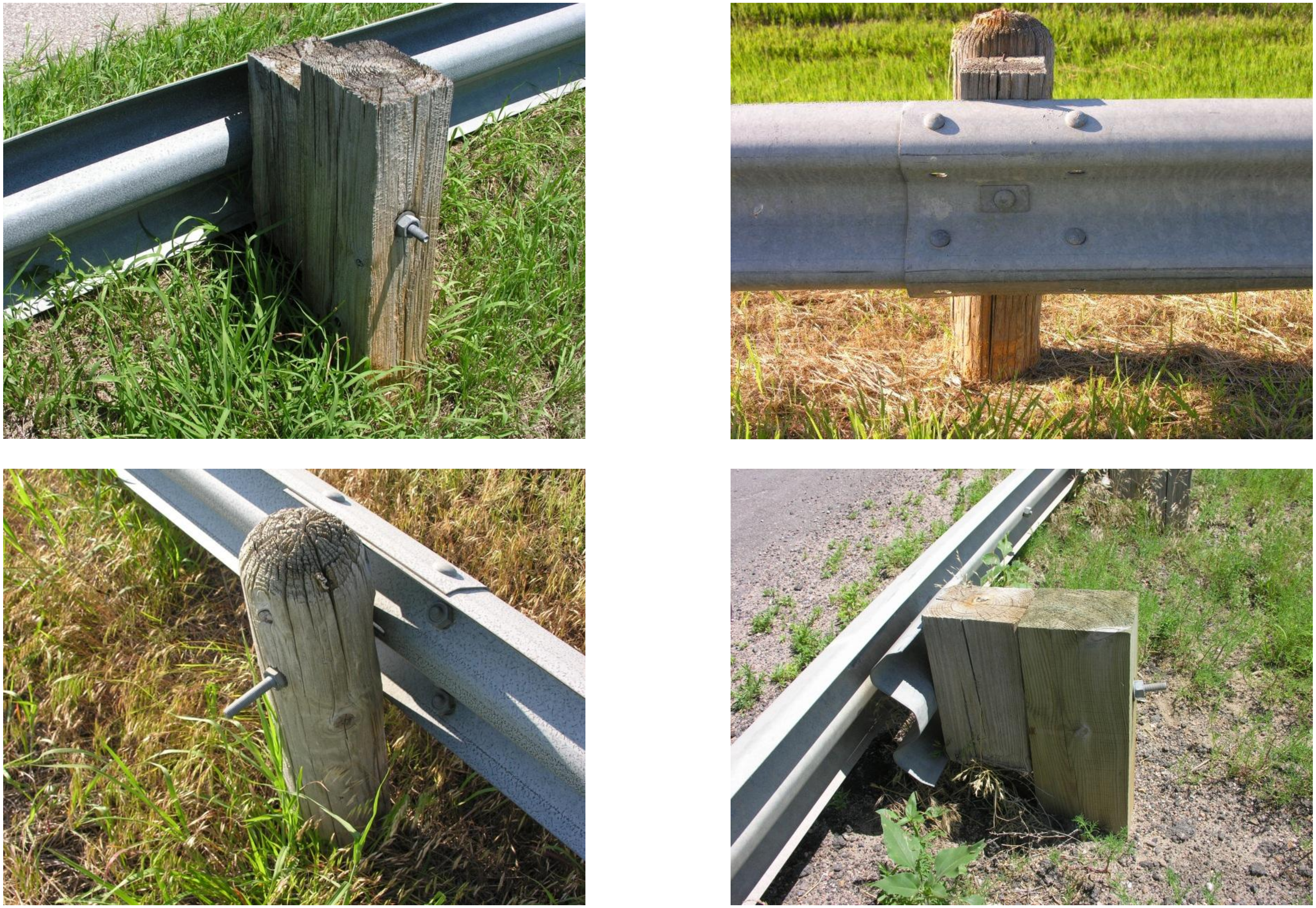

Figure 11. Examples of Existing W-Beam Guardrail Systems

Figure 12. Examples of Existing W-Beam Guardrail Systems

3.2.2 Existing W-Beam Guardrail Height

In the field investigation, the maximum and minimum top rail heights were measured for each guardrail system. These height measurements were taken from the top of the rail to the ground as well as from the top of the rail to the roadway surface at the edge of travel lane, as shown in Figures 13 and 14. When compared to the recommended 31-in. (787-mm) top-rail mounting height, the W-beam heights found in the field investigation are very low and a potential cause of concern. The mean, standard deviation, and range of the guardrail heights at the face of the rail and relative to roadway are shown in Table 5. Examples of W-beam guardrail found with low rail height are shown in Figure 15.

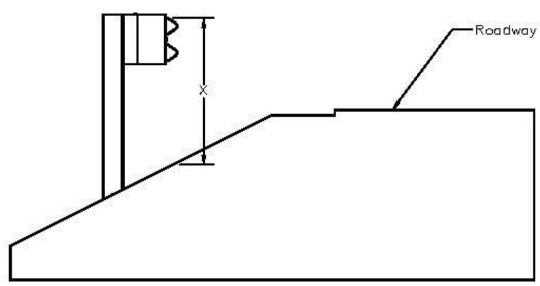

Figure 13. Guardrail Height Measured to the Ground at Rail Face

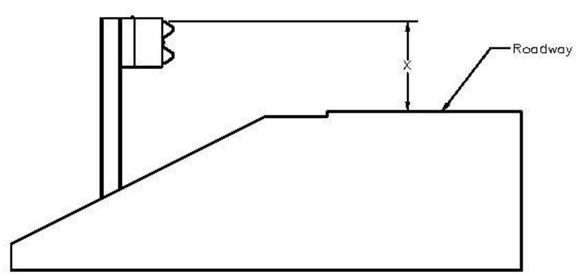

Figure 14. Guardrail Height Measured to the Ground at Roadway Edge

Table 5. Summary of Guardrail Heights from Field Investigation

	Guardrail Height							
	Ground at Face of Barrier				Ground at Roadway Edge			
	Minimum		Maximum		Minimum		Maximum	
	(in.)	(mm)	(in.)	(mm)	(in.)	(mm)	(in.)	(mm)
Average	21.8	555	26	659	10.4	264	16.9	428
Range	11 to 32	279 to 813	17 to 52	432 to 1,321	-16 to 26	-406 to 660	6 to 30	152 to 762
Standard Deviation	4.8	122	5.5	141	7.8	199	5.3	134

3.2.1 W-Beam Guardrail End Terminals

As noted previously, the W-beam guardrail end treatments found at the selected sites were the spoon (blunt-end) and turned-down (sloped-end) terminals. These terminal types are not acceptable according to the TL-3 safety performance criteria found in NCHRP Report No. 350 or MASH. A fishtail or spoon terminal acts as a blunt-end which can spear into the occupant compartment of errant vehicles. As observed in the field investigation, many of these blunt-end terminals lacked the proper tensile anchorage to adequately contain and redirect errant vehicles which impact the barrier system away from the ends. The turned-down terminal was developed to eliminate the potential for the

Figure 15. Examples of Low Heights for Existing W-beam Guardrail Systems

rail to spear into the passenger compartment of an impacting vehicle, which was a significant improvement over the blunt-end. However, the slope end acted as a ramp and allowed impacting vehicles to climb the rail, become airborne, and rollover. In some cases, the airborne vehicles impacted the vertical hazards that were to be shielded by the guardrail under high-speed impact conditions. An errant vehicle impacting either of these non-crashworthy terminals may likely cause a more severe accident than striking the unshielded hazard itself.

3.2.2 B-beam Guardrail to Bridge Rail Transition

W-beam guardrail to bridge rail transitions were included in the field investigation and were found to deviate from current standard practice at many of the old sites. Some existing W-beam guardrails were not connected to the bridge rail ends. In most cases, an errant vehicle could likely contact the end of the rigid bridge rail. This heavy contact and inadequate vehicle redirection would likely result in snag on the bridge rail end with large decelerations and increased occupant risk. Approach guardrail transitions have been developed and successfully crash tested by using reduced post spacing, stronger or longer posts, stacked or nested rail elements, and gradual changes in lateral barrier stiffness and strength. Examples of W-beam guardrail to bridge rail transitions that were found in the field investigation are shown in Figure 16.

3.2.3 Insufficient Length of Need

Guardrails are intended to protect motorists from roadside hazards, even when vehicles inadvertently leave the roadway upstream of the hazard and would be unable to avoid that hazard. The section which shields these motorists from the hazard is known as the length of need. Guardrail length of need consists of two guardrail sections: the length

Figure 16. Examples of Existing W-beam Guardrail to Bridge Rail Transitions

of the crashworthy terminal section capable of redirecting or containing the errant vehicle and the remaining standard guardrail that is required to meet the length of need. Many of the guardrails found in the field investigation had a much shorter length of need than recommended. Some culverts only had guardrails on top of them, thus producing no upstream guardrail to shield errant vehicles from the hazard.

3.2.4 Existing Barrier System Damage

State and federal agencies have limited funds and resources to repair all damage observed in a guardrail system. It is important to know what types of damage need immediate attention. System damage can be caused by prior vehicle crashes, maintenance equipment (snow plows and mowers), and corrosion to name a few. The system damage found in the field investigation included missing posts, missing blockouts, missing splice bolts, minor and major rail damage, minor corrosion of steel barrier hardware, and weathering of wooden posts. FHWA's *W-Beam Guardrail Repair-A Guide for Highway and Street Maintenance Personnel* informs highway officials when to repair damaged guardrail [43]. This guidance is helpful when evaluating a guardrail installation that is not substandard in any other way. The following sections describe the guardrail damage found in the field investigation. Engineering judgment should be used to evaluate when to repair, remove, or replace the existing barrier system if there is damage or other deviations from the standard design. When a system is damaged extensively, the entire barrier is often updated to the current standards. This practice also should also be considered when a system is found with different levels of system damage.

3.2.4.1 W-Beam Rail Damage

Damage on rail caused by previous impacts will most likely require repair unless the damage is minor. Scratches, small dents, and kinks can be considered to be minor in many circumstances. Major damage can be characterized by tears, cuts, major folds, and bends to name a few. Again, the *W-Beam Guardrail Repair Guide* and engineering judgment should be used when considering which of these systems would require repair and which are still crashworthy. Examples of rail damage found on existing W-beam guardrail systems are shown in Figure 17.

3.2.4.2 Missing Hardware

Missing splice bolts was another type of rail damage documented in the field investigation. Missing splice bolts and other small components was frequently observed on the W-beam guardrail systems. Out of the 45 W-beam barriers, 12 systems had missing bolts at one or more splice locations. Splices are considered to be a weak point of a guardrail system, and missing splice bolts increase the risk of rail rupture at the splice location. This finding will increase the potential for vehicles to penetrate the rail and interact with the hazard, which the rail is supposed to shield. Missing splice bolts can be caused by poor construction, inspection, and maintenance practices. In the field investigation, many of the guardrail splices were missing four bolts. This is a major cause of concern.

3.2.4.3 Post Damage

Missing posts are a common deviation from the standard design in existing guardrail systems. Posts can be missing or and/or ineffective because of prior impacts, snowplow damage, rotting wood, insect damage, frost uplift, and faulty construction.

Figure 17. Examples of Rail Damage in Existing W-Beam Guardrail Systems

A system with one or two missing posts may function adequately under a majority of vehicle impacts [43-44]. Thus systems with three or more missing posts should be considered for immediate repair. This finding is not to say that a system with a missing post doesn't need repair. All existing guardrail systems with missing a post need to be repaired for the barrier to act as intended. Examples of this deficiency are shown in Figure 18.

Many wooden posts found in the field investigation were weathered or rotting. This type of system damage can occur due to normal environmental conditions. Although these posts with superficial damage may appear weaker, they potentially may retain much of their structural integrity and possibly not require repair. When significant rotting of wood material is found on multiple posts, repair or replacement of the barrier is necessary. Examples of weathered or rotting wood posts are shown in Figure 19.

3.2.4.4 Blockout Damage

Many blockouts found in the field investigation were weathered, rotting, rotated off center, or absent from the system at various post locations, with the most critical state being missing blockouts. Blockouts extend the W-beam rail element away from the posts to mitigate the amount of wheel snag on the posts as well as maintain rail height. Missing blockouts may cause a guardrail to deviate from the expected barrier performance. Blockouts can be missing from a system because of prior impacts, snowplow damage, material rotting, insect damage, and/or faulty construction. A guardrail system with a missing blockout will not perform as well as a fully repaired system. Its performance, however, potentially may be comparable to a system with no missing blockouts [44]. For this reason, missing blockouts should be a cause of concern on existing W-beam

Figure 18. Examples of Missing and Inadequate Posts

Figure 19. Examples Weathered and Decaying Post in Existing Barrier Systems

guardrail systems, but it does not require immediate repair. Systems with missing blockouts from the field investigation are shown in Figure 20.

FHWA's *W-Beam Guardrail Repair Guide* should be used for all damaged guardrails when no other deviations from standard practice are found, such as low top-rail heights and outdated end treatments. Engineering judgment and analyses laid out in Chapters 8 and 9 should be used if a guardrail installation has both system damage described in this section and other deviations from the standard design described in this chapter on whether to replace, remove, repair, or do nothing to the existing barrier system. The assessment of repairing damaged guardrail should include hazard exposure, hazard severity, severity of guardrail damage, guardrail hardware utilized, and agency resources.

3.3 Cable Barriers

Out of the 68 barrier systems documented during the field investigation, 9 were cable barrier systems. The cable barriers were either two-cable low-tension systems (8 systems) or single-cable low-tension systems (1 system). The cables were generally in good condition. All of the cable systems had wooden posts, and one system incorporated both concrete and wood posts. The round and rectangular wood posts had typical cross sections of 7 in. (178 mm) diameter and 5½ in. x 7½ in. (140 mm x 191 mm), respectively. For the most part, the wood posts were in good condition with some weathering and decay below the ground line. The concrete posts had a cross section of 6 in. x 6 in. (152 mm x 152 mm). The post spacing for the cable barriers was 12 ft - 6 in. (3.8 m) for 8 systems and 10 ft (3.0 m) for 1 system. All systems used a large steel cable-to-post bracket. The longer barrier systems utilized 400-ft (121.9-m) cable segments,

Figure 20. Examples Missing Blockouts in Existing Systems

3.4 which were not connected to each other. The cable systems were used to shield roadside slopes and culvert openings. A summary of the cable barrier systems that were documented during the field investigation is shown in Miscellaneous Barrier Systems

Out of the 68 barrier systems documented, 14 were classified as “Miscellaneous” and are shown in Table 7.

3.4.1 Wood, Strong-Post Modified W-Beam Guardrail Systems

Out of these 14 systems, 9 were wood, strong post systems which resembled standard W-beam guardrails but early versions. The rail was similar to standard W-beam rails, but it had a few variations. The upper and lower edges of the modified W-beam

Table 6. Photographs of various documented cable barriers are shown in Figures 21 through 23.

In general, cable barrier systems redirect errant vehicles through the use of various mechanisms, including post bending or fracture, axial stretch of the cables, and work done by frictional losses between the vehicle and barrier components. The documented cable barrier systems had many deviations from standard cable barriers. Most cables had kinks, slack (non-tensioned) spans, and corroded components. The concrete posts would become blunt hazards to motorists, if impacted. The end sections of the existing barrier systems had two major concerns: (1) they did not have sufficient anchorage to produce enough strength on the ends of the cable systems to redirect an errant vehicle and (2) the end posts were exposed to errant vehicles, presenting a blunt end hazard. Missing posts were also found within the systems. The use of only 1-cable or 2-cable systems may pose a risk of not being able to safely contain or redirect an impacting vehicle.

3.5 Miscellaneous Barrier Systems

Out of the 68 barrier systems documented, 14 were classified as “Miscellaneous” and are shown in Table 7.

3.5.1 Wood, Strong-Post Modified W-Beam Guardrail Systems

Out of these 14 systems, 9 were wood, strong post systems which resembled standard W-beam guardrails but early versions. The rail was similar to standard W-beam rails, but it had a few variations. The upper and lower edges of the modified W-beam

Table 6. Summary of Existing Cable Barrier Systems - Design Details

System No.	Post Material	Terminal Type	Barrier Length		Barrier Offset		Post Spacing	
			(ft)	(m)	(in.)	(mm)	(in.)	(mm)
46	wood	none	100	30.5	10	254	150	3,810
47	wood	none	300	91.4	128	3,251	150	3,810
48	concrete/ wood	none	454	138.4	59	1,499	120	3,048
49	wood	none	153	46.6	127	3,226	150	3,810
50	wood	none	501	152.7	12	305	150	3,810
51	wood	none	605	184.4	9	229	150	3,810
52	wood	none	5,280	1,609.3	114	2,896	150	3,810
53	wood	none	402	122.5	78	1,981	150	3,810
54	wood	none	298	90.8	97	2,464	150	3,810

were vertical rather than horizontal. Also, the modified W-beam splices utilize only three ⅝ in. (16 mm) bolts, instead of eight. The systems utilized both round and rectangular wood posts, which had typical cross sections of a 6 in. diameter (152 mm) and 5½ in. x 7½ in. (140 mm x 191 mm), respectively. Only three of the nine systems had wood blockouts. The remaining systems did not use blockouts. Spoon terminals were the only end treatment found on all these modified W-beam barriers, which act as blunt ends to impacting vehicles. Also, none of these end terminals provided any type of anchorage, giving them little redirective strength to resist an impacting vehicle. Three of the nine systems utilized 6 ft - 3 in. (1.9 m) post spacings. The rest had 12 ft - 6 in. (3.8 m) spacings. The modified W-beam guardrail systems shielded slope and culvert hazards. Typically, these systems had a top rail height ranging from 11 in. to 29 in. (279 mm to 737 mm), with an average of 21.7 in. (551 mm) when measuring the lowest point of each barrier system. Photographs of these systems are shown in Figure 24.

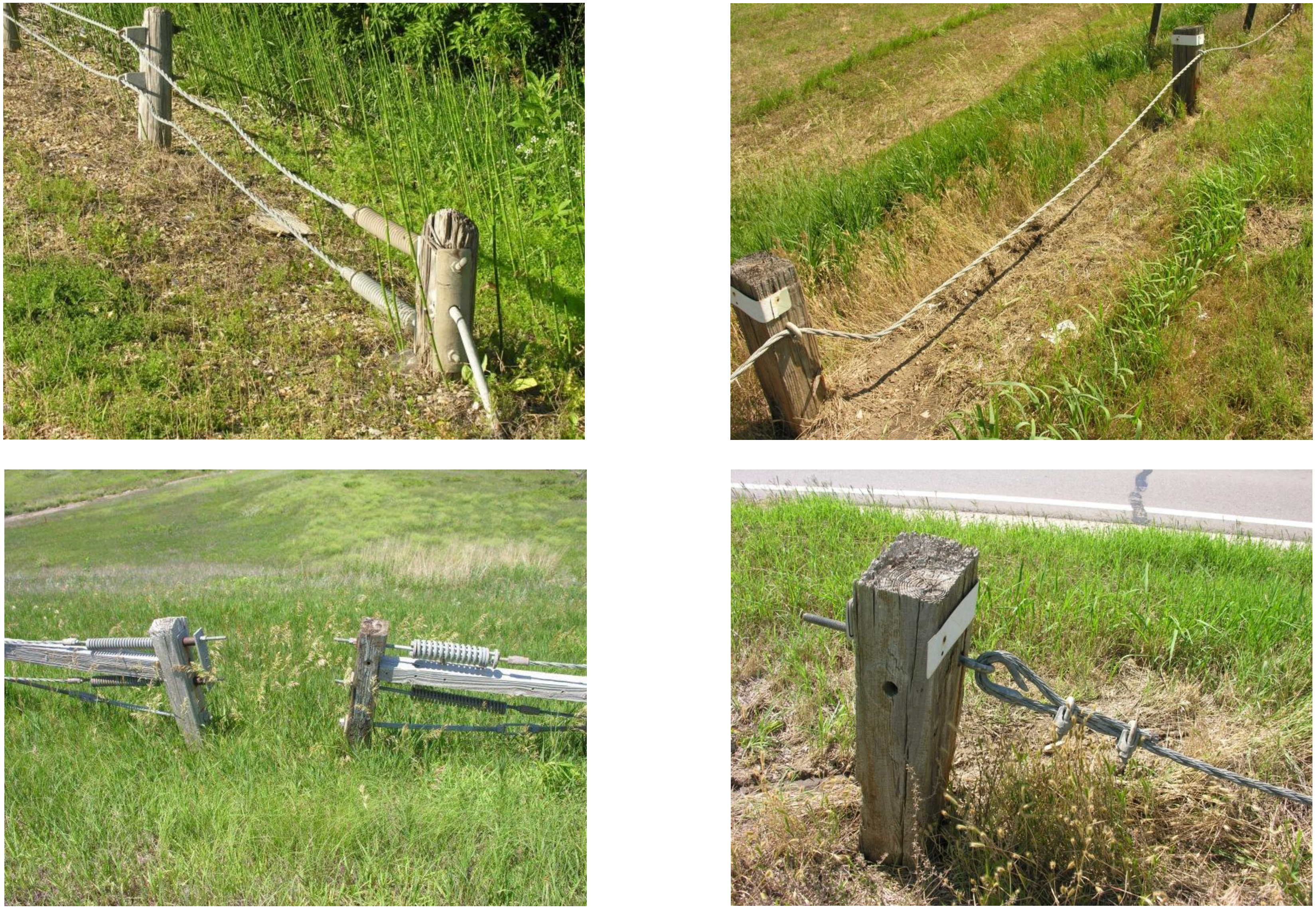

Figure 21. Examples of Deviations from Cable Barrier Systems

Figure 22. Examples of Deviations from Cable Barrier Systems

Figure 23. Examples of Deviations from Cable Barrier Systems

Table 7. Miscellaneous Barrier Parameters from the Field Investigation

	System Description	Post Material	Blockout Material	Terminal Type	Barrier Length		Barrier Offset		Post Spacing	
					(ft)	(m)	(in.)	(mm)	(in.)	(mm)
55	Strong-Post Modified W-Beam	wood	wood	spoon	125	38	NA	NA	75	1,905
56	Strong-Post Modified W-Beam	wood	wood	spoon	100	30	NA	NA	75	1,905
57	Strong-Post Modified W-Beam	wood	wood	spoon	137	42	26	660	75	1,905
58	Strong-Post Modified W-Beam	steel/wood	spoon	spoon	27	8	56	1,422	150	3,810
59	Strong-Post Modified W-Beam	wood	spoon	spoon	425	130	20	508	150	3,810
60	Strong-Post Modified W-Beam	wood	spoon	spoon	350	107	47	1,194	150	3,810
61	Strong-Post Modified W-Beam	wood	bend	bend	53	16	60	1,524	150	3,810
62	Strong-Post Modified W-Beam	wood	bend	bend	190	58	59	1,499	150	3,810
63	Strong-Post Modified W-Beam	wood	spoon	spoon	76	23	48	1,219	150	3,810
64	Strong-Post Channel Rail	steel	spoon	spoon	10,560	3,219	0	0	150	3,810
65	Strong-Post–Flat-Panel	wood	steel	none	64	20	4	102	192	4,877
66	Strong-Post–Flat-Panel	wood	steel	none	64	20	7	178	192	4,877
67	Strong-Post–Flat-Panel	wood	steel	none	273	83	66	1,676	192	4,877
68	Concrete Post and Rail	concrete	NA	none	NA	NA	NA	NA	48	1,219

NA – Not able to document due to roadway conditions and/or other circumstances

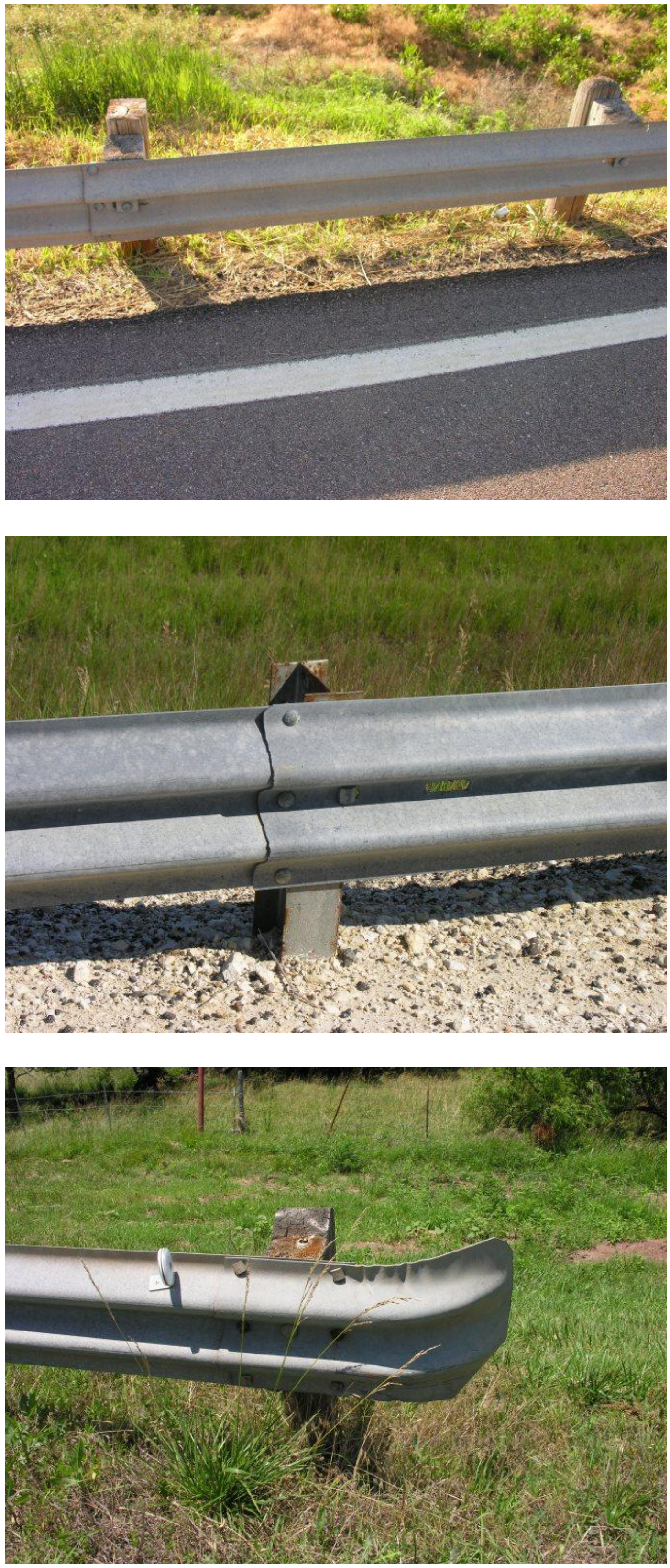

Figure 24. Examples of Deviations from Standard W-Beam Guardrail Systems

3.5.1 Steel, Flat-Panel Systems

Three of the 68 barrier systems documented were steel, flat-panel barriers. This barrier utilized a steel panel rail with an average thickness of 0.126 in. (3.2 mm). The flat-panel system used rectangular 5-in. x 7-in. (127-mm x 178-mm) wood posts with circularly looped, steel tube blockouts. The rail was spliced at each post with two steel ½-in. (13-mm) diameter pins. The upstream and downstream end treatments of all flat-panel systems were blunt ends with little or no anchorage. All three flat-panel systems were shielding slopes. Examples of the flat-panel systems are shown in Figure 25.

3.5.2 Channel Rail System

One barrier documented during the field investigation was regarded as a channel rail. The barrier appeared to be in good condition. The steel channel barrier was very similar to a standard W-beam guardrail and utilized steel W6x9 (W152x13.4) posts. Post spacing for the channel rail was 12 ft - 6 in. (3.8 m). Two steel brackets separated the rail from the posts. The upstream and downstream end treatments of the channel rail were blunt ends with no anchorage. Rail splices were located at each post location with twelve ⅝-in. (16-mm) splice bolts. The steel channel rail shielded the slope of a dam. Photographs of the channel rail system are shown in Figure 26.

Figure 25. Examples of Flat-Panel Systems

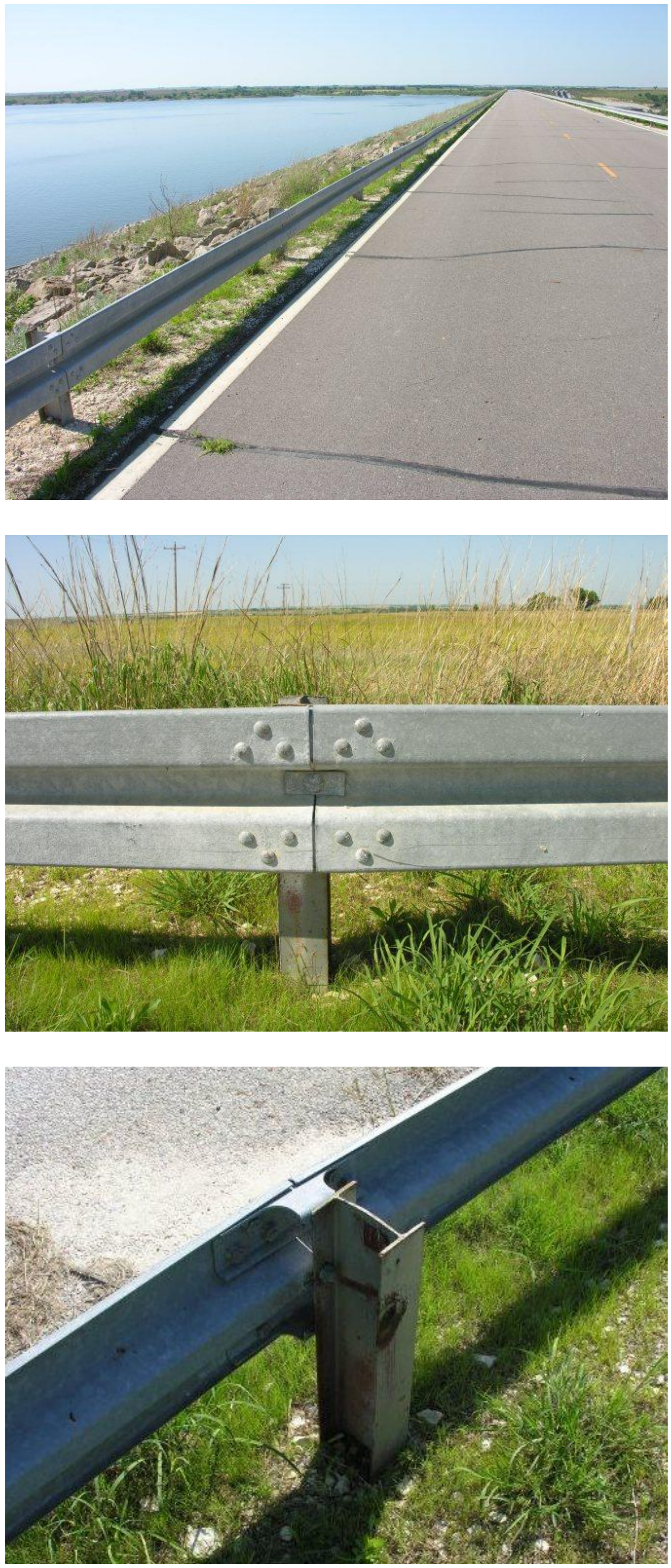

Figure 26. Examples of Channel Rail Systems

3.5.1 Concrete Post and Rail System

One concrete rail with concrete posts over a culvert was discovered in the field investigation. The barrier was in good condition with minor cracks. The posts were 12 in. x 9 in. x 39 in. (305 mm x 229 mm x 991 mm) with a 48-in. (1,219-mm) post spacing. The barrier was not equipped with an end treatment. This barrier could pose a more severe hazard than the hazard it is shielding. Photographs of the concrete post and rail system are shown in Figure 27.

Figure 27. Examples of Concrete Post and Rail System

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4 ROADSIDE ANALYSIS PROGRAM (RSAP)

4.1 RSAP Overview

RSAP provides a benefit-to-cost analysis procedure for use in developing general guidelines and best practices for upgrading existing barrier systems [11]. RSAP utilizes a probability-based approach to predict vehicle encroachments, impacts, and severities. RSAP predicts the benefits of reducing injuries and fatalities along with the costs of installation and forecasted repairs to the safety devices utilizing the Monte Carlo simulation technique. The Monte Carlo technique generates average impact conditions, such as impact speed and angle, for a particular set roadway conditions. From this impact severity, accident costs for a particular roadside condition can be determined. The benefits are defined as reduction in injuries and fatalities as a unit of cost. If the benefits of a particular system outweigh its costs, then that barrier alternative is recommended for use at that particular site. RSAP is also able to examine multiple alternatives at once, making it possible to select the optimum solution from various treatment options. The general formulation for the B/C method used in RSAP is shown in Equation 1.

$$B/C\ Ratio_{2-1} = \frac{AC_1 - AC_2}{DC_2 - DC_1} \tag{1}$$

Where,

$B/C\ Ratio_{2-1}$ = Incremental B/C ratio for Alternative 2 to Alternative 1

AC_1, AC_2 = Annualized societal crash cost for Alternative 1 and Alternative 2, respectively

DC_1, DC_2 = Annualized direct costs for Alternatives 1 and Alternative 2, respectively

The encroachment module used in RSAP was based on a study conducted by Cooper in the late 1970's [10]. This study was performed by collecting encroachment data from off-road tire tracks. The results of the Cooper data are shown in Figure 28. There were two major concerns from this study. First, there were no recorded encroachments less than 13.1 ft (4 m) laterally due to paved shoulders. The re-analysis of the Cooper encroachment data on the extent of lateral encroachment involved fitting a regression model to lateral extent data beyond 13.1 ft (4 m). The results of the lateral extent data regression is shown in Figure 29. From these results, it was estimated to increase the encroachment frequencies by a ratio of 2.466 on two-lane undivided highways [11]. A

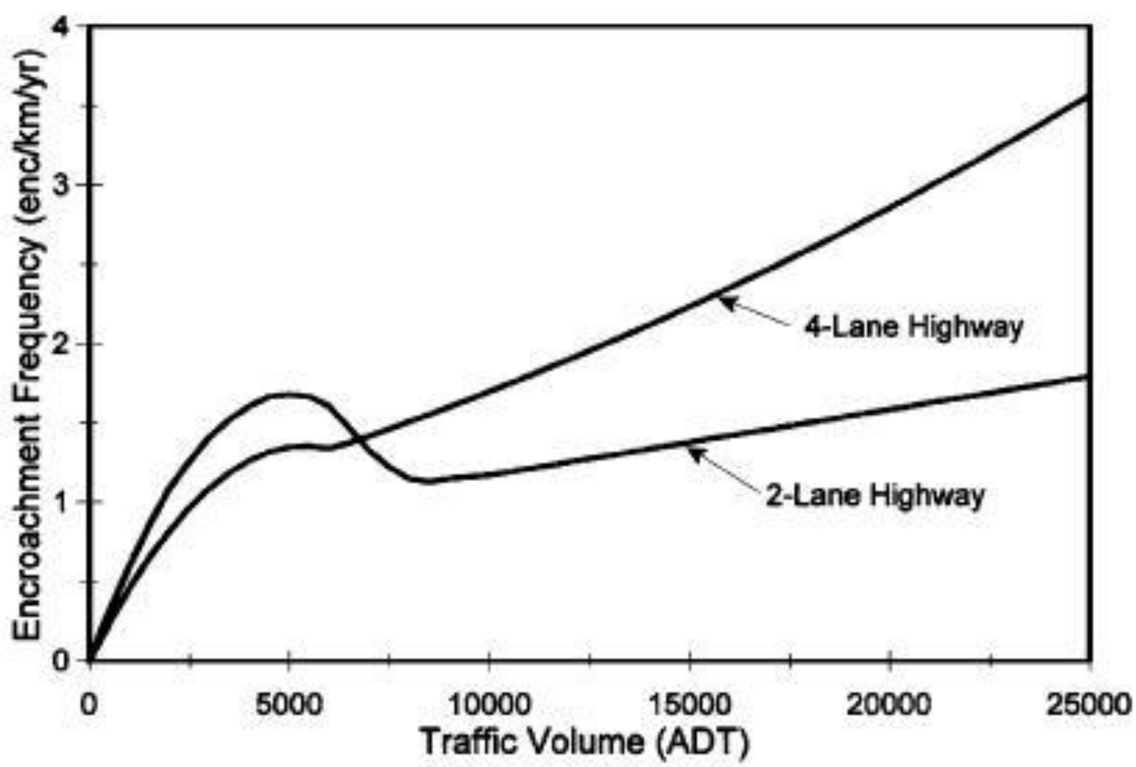


Figure 28. Encroachment Rates from Cooper [10]

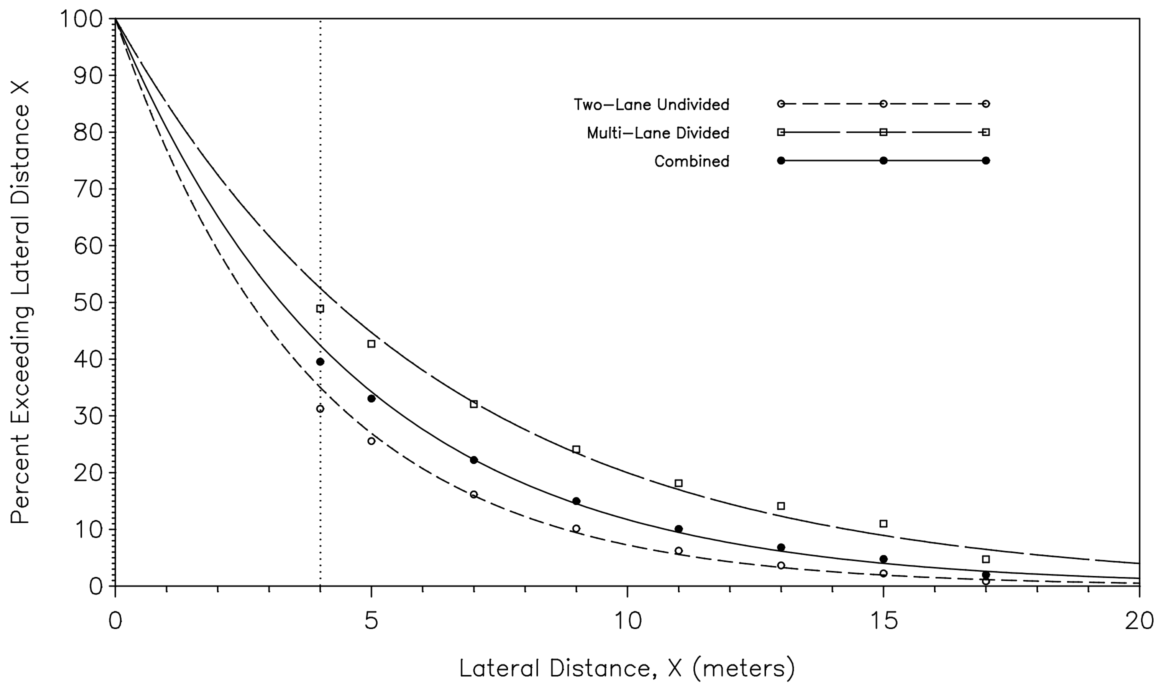


Figure 29. RSAP Lateral Extent of Encroachment Distribution [10]

separate study was used to distinguish controlled and uncontrolled encroachments [49]. A controlled encroachment occurs when a driver purposefully drives off the travelway for a particular reason, such as pulling over to look at a map. This consideration would then reduce the amount of uncontrolled encroachments. It was estimated that encroachment frequency was multiplied by a factor of 0.60 to account for this issue.

From the encroachment module, an impact into a roadside feature may be predicted during the crash prediction module. This can be determined by the trajectory (i.e., speed, angle, and location) of the errant vehicle from the roadway and location of the defined hazard. If a hazard was in the path of an encroaching vehicle, an impact was predicted. Each hazard is defined with a containment value. In RSAP, this value can determine if the errant vehicle has enough energy to penetrate through a hazard or barrier and interact with objects placed behind. This was a very important occurrence when modeling barriers with deviations from their standard configurations.

When RSAP generates a predicted accident from the encroachment probability, it must also have an associated calculated cost of the accident. This is done using the severity of the crash (i.e. severity level). The severity level is found by developing a link between vehicular impact conditions and the Severity Index (SI) of the hazard or barrier. SI is a scale of crash severity ranging from 0 (no damages) to 10 (100 percent fatality rate). RSAP attempts to assign an SI value for each predicted impact based upon the predicted speed, impact angle, and the hazard struck. The SI values are based on percentages of injury levels of impacts as incorporated into RSAP, as shown in

Table 8.

Finally, a benefit-to-cost module was developed. This was based on the results of the preceding modules (encroachment, crash prediction, and severity modules). The benefit-to-cost module compares the direct and accident costs from a number of alternatives to develop a guideline based on the input data.

4.2 Problems in RSAP

The RSAP program is currently being updated in NCHRP Project No. 22-27. During the research effort to update the current RSAP program, Dr. Malcolm Ray found many discrepancies, bugs, and errors in the RSAP code. Discrepancies occurred when information from the RSAP Engineering Manual [11] or the RSAP User Manual [50] differs from the actual program. Bugs are faulty programming logic. Problems are mistakes made in the code. All of these problems in RSAP may lead to inaccurate results. A complete list of the discovered discrepancies, bugs, and errors are shown in the draft report of NCHRP

Table 8. Injury Level Percentages for Each Severity Index [11]

Severity Index (SI)	Injury Level (%)						
	None	PDO1	PDO2	C	B	A	K
0	100.0	-	-	-	-	-	-
0.5	-	100.0	-	-	-	-	-
1	-	66.7	23.7	7.3	2.3	-	-
2	-	-	71.0	22.0	7.0	-	-
3	-	-	43.0	34.0	21.0	1.0	1.0
4	-	-	30.0	30.0	332.0	5.0	3.0
5	-	-	15.0	22.0	45.0	10.0	8.0
6	-	-	7.0	16.0	39.0	20.0	18.0
7	-	-	2.0	10.0	28.0	30.0	30.0
8	-	-	-	4.0	19.0	27.0	50.0
9	-	-	-	-	7.0	18.0	75.0
10	-	-	-	-	-	-	100.0

Where,

PDO1 = Property Damage Only (Level 1)
PDO2 = Property Damage Only (Level 2)
C = Possible or Minor Injury
B = Moderate Injury
A = Severe Injury
K = Fatal Injury

Project No. 22-27 [51]. The discovered problems were determined to be insignificant in the scope of this project. As such, the original RSAP program was continued for this study but with accommodating some of the known concerns.

RSAP (Version 2003.04.01) [11] incorporates two integrated programs, the Main Analysis Program and the User Interface Program. This user interface provides a user-friendly environment for data input and review of the program results from data files. One of these files is called “road.dat,” which contains parameters to model the roadway, such as functional class, number of lanes, lane width, speed limit, segment length, and horizontal/vertical curve information. The functional class is determined by a two-digit number, which was then used by the Main Analysis Program to determine the speed and angle of the vehicle encroachments. The functional class selected in the user interface differs from the Main Analysis Program, as shown in Table 9. Rural arterials were the only functional class used in this project, which was determined later in this report. Thus, this problem was found to be insignificant in the scope of this project.

Table 9. Functional Class Code Differences

Functional Class	User Interface	Analysis Program
Freeway	22	21
Urban Arterial	25	12
Urban Local	24	15
Rural Arterial	22	22
Rural Local	21	25

5 CONSTANT RSAP MODELING PARAMETERS

5.1 Societal Costs

RSAP has two predefined sets of accident crash costs from the RDG and FHWA. These costs are intended to associate a dollar value to societal costs for an accident resulting in a certain injury level. The RDG accident costs are not considered to be comprehensive and do not include all factors, such as a person's willingness to pay to improve safety (i.e. avoid injury or fatality). The FHWA values are based on the 1994 U.S. dollar. However, adjustments have been made in a previous study, namely the 2009 FHWA's *Highway Safety Improvement Program Manual,* as shown in Table 10 [52]. These values were incorporated into RSAP for this study.

Table 10. FHWA's 2009 Comprehensive Accident Costs [52]

Accident Type	Accident Costs ($)
Fatal	4,008,900
Severe Injury	216,000
Moderate Injury	79,000
Minor Injury	44,900
Property Damage Only	7,400

5.2 Highway Modeling

5.2.1 Sensitivity Analysis

The roadway sections implemented into RSAP were modeled to represent the rural Kansas highways that were documented in the field investigation. Three steps were used to best determine how each roadway feature was modeled. First, the results from the field investigation were analyzed to determine the common roadway features found.

Next, a sensitivity analysis was performed in RSAP to conclude if the roadway feature differences had a substantial effect on the accident cost. This analysis was completed setting all variables pertaining to the roadway, hazard, and barrier constant in RSAP to a standard base condition and then changing one roadway parameter to see how or if it affected the results. The variables subjected to the sensitivity analysis were chosen from what was found in the field investigation and team discussion. The roadway conditions were modeled with a TL-3 W-beam guardrail and a culvert opening model on rural arterial highway to generate accident costs. The roadway variables examined in the sensitivity analysis and results are shown in Table 11. If the feature parameters had little difference to the baseline, only a few or one value was used for that variable in the final RSAP set. The last step in modeling the RSAP runs was a team discussion. In the discussion, the final roadway constraints were determined based on the field investigation, sensitivity analysis, and engineering judgment, as described in this section.

5.2.2 Highway Type

All roadways documented in the field investigation were two-lane roadways without medians. Around 90 percent of the roadways were minor arterial roadways, as defined by Kansas DOT. For these reasons, two-lane undivided, minor arterial roadways were the highway type selected for the RSAP analysis.

Table 11. Roadway Sensitivity Analysis - Parameters and Results

Road Parameters	Base Condition	Changed Condition	Estimated Annual Crash Costs (USD)	Percentage Change
Base	Base	None	$14,326	NA
ADT	5,000	1,000	$5,041	-64.8%
	5,000	25,000	$15,299	+6.8%
Horizontal Curve	No Curve	5 Degree Right	$19,536	+36.4%
	No Curve	5 Degree Left	$33,156	+131.4%
Lane Width	12 ft (3.7 m)	10 ft (3.0 m)	$15,614	+9.0%
	12 ft (3.7 m)	11 ft (3.4 m)	$15,242	+6.4%
Shoulder Width	2.5 ft (0.8 m)	0 ft (0.0 m)	$14,326	0.0%
	2.5 ft (0.8 m)	12 ft (3.7 m)	$14,326	0.0%
Vertical Grade	No Grade	3% Downgrade	$15,630	+9.1%

5.2.3 Lane Widths

As previously noted, lane widths were typically 12 ft (3.7 m). However, some roadways had lane widths of 9 ft (2.7 m). Distributions of lane widths found in the field investigation are shown in Figure 30. The sensitivity analysis showed little variation in the results when changing the typical lane with of 12 ft (3.7 m) to 10 ft (3.0 m) and 11 ft (3.4 m) (both less than 10 percent change). For this reason, only roadways with 12 ft (3.7 m) lane widths were considered.

5.2.4 Shoulders

All roadways had paved surfaces in the field investigation. Only one documented barrier type had a paved shoulder adjacent to the roadway. The width of grass and gravel shoulders was documented. After conducting a sensitivity analysis of different shoulder widths, it was found that they did not significantly influence the results. Therefore, shoulders were omitted from the B/C analysis. These values were just considered as part of the lateral offset of the existing W-beam guardrail system in the RSAP analysis from the roadway.

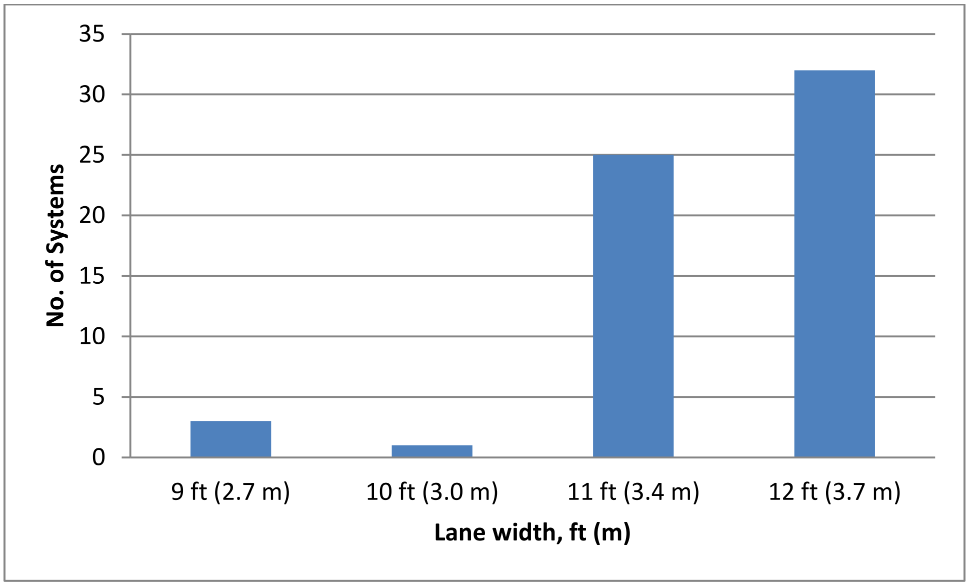


Figure 30. Lane Width found in Field Investigation

5.2.5 Speed Limit

The speed limit is another input to consider in RSAP. As previously noted, the posted speed limits found on these roadways varied from 35 mph to 65 mph (56.3 km/h to 104.6 km/h), as shown in Table 12. Although most roadways had a 65-mph (104.6-km/h) speed limit, the speed data in RSAP was based on the Cooper encroachment study, which was completed when the national speed limit was set at 55 mph (88.5 km/h) [10]. As a result, speeds above 55 mph (88.5 km/h) are not considered to be modeled correctly. Thus, all RSAP models were set with a 55 mph (88.5 km/h) speed limit.

Table 12. Distribution of Speed Limits Found in the Field Investigation

Speed Limit	mph	65	60	55	50	45	40	35
	km/h	104.6	96.6	88.5	80.5	72.4	64.4	56.3
No. of Systems		43	3	8	1	3	2	1

5.2.6 Average Daily Traffic (ADT)

As previously noted, the ADT on the roadways that were documented in the field investigation ranged from 300 to 11,000 vpd. The ADT has a big influence of the accident frequency in RSAP, as shown from the sensitivity analysis results (64.8 percent change from 5,000 to 1,000 vpd). After completing the sensitivity analysis and team discussion, ADTs of 500, 1,000, 5,000, 10,000, and 25,000 vpd were chosen for the RSAP analysis based on the significant changes in the sensitivity analysis.

5.2.7 Other Roadway RSAP Parameters

The nominal percentage of trucks was set to 2 percent. Traffic growth factor was set to zero, and the encroachment rate adjustment factor was left unchanged at the default value of 1. Default values of 25 years and 4 percent were used for the design life and discount rate, respectively.

5.3 Segment Modeling

5.3.1 Segment Length

The length of the evaluated road was 3,281 ft (1,000 m) long. This would allow for a longitudinal provision for the clear area on either side of the downstream and upstream guardrail terminals.

5.3.2 Vertical Grade

There were vertical grades reported in the field investigation, but no values were recorded. From results of the sensitivity analysis, the change from flat ground to a 3 percent down grade was under 10 percent. After team discussion, it was determined to leave vertical grade out of the RSAP analysis, and only flat ground was considered.

5.3.3 Horizontal Curvature

The final criteria to consider in segment modeling were horizontal curves. Although only 9 of the 68 barriers in the field investigation had a horizontal curve, it was still determined by the sensitivity analysis and group discussion that implementing a curve for the RSAP analysis was needed. RSAP only analyzes traffic in one direction, so it is important to find which direction of curvature would make the most severe roadside conditions. Left-hand curves were more severe than right due to increased encroachment frequency, as shown in the sensitivity analysis (5 degree left-hand turn resulted in a 131.4 percent increase in accident costs). So a typical 5-degree left curve, or 1,146-ft (349-m) radius curve, and a straight roadway segment were used in the RSAP models.

6 BARRIER AND HAZARD SELECTION

6.1 Introduction

RSAP has the ability to evaluate many different roadway conditions, barriers, and hazards. In order to best evaluate existing guardrail systems and keep the RSAP evaluation matrix manageable, the amount of variables had to be limited to only the most critical. Thus, the most prominent and severe features found in the field investigation were selected to be evaluated in RSAP.

6.2 Hazard Selection

The selection of a representative hazard was based on the number of occurrences, the severity of the hazard, and the relative distance between the feature and the edge of roadway. It was important to select hazards which would encompass most situations, yet still keep the RSAP evaluation matrix manageable in size. Common roadside hazards that were shielded by existing barriers on Kansas DOT highways included culvert openings, roadside slopes, bridge rail ends, small waterways, and trees.

The trees and waterway hazards were only documented at one guardrail location. In light of the limited exposure in the field investigation, these two hazards were omitted from further analysis.

All documented bridge approach guardrail (i.e. transitions) utilized a W-beam guardrail connected to a concrete bridge rail. These stiffness transition systems had many deviations from current standard practice for W-beam guardrail transitions. Blunt-end terminals were the only end treatments found at the locations of the bridge approach guardrails that were included in the field investigation. The approach guardrail normally included two steel posts bolted to a bridge curb, which were used to extend the W-beam rail past the end of the concrete bridge rail. However, the W-beam rail was rarely anchored to the concrete bridge parapet in a proper manner. No W-beam guardrail stiffening was used, such as reduced post spacing or increased post size. For these reasons, it can be expected that most high-speed impacts into these approach barriers would result in high severity crashes. The analysis of bridge transitions was left out of the RSAP analysis. Due to the deficiencies, it was recommended that all non-crashworthy transition and end terminal systems be upgraded with those systems that meets current impact safety standards.

From the field investigation, culvert openings and roadside slopes were the most prominent hazards that were shielded by an existing barrier system with documented deviations from standard practice. Both hazard types were found near the traveled way and are easily modeled using predefined features within RSAP. The culvert structures varied in length, drop height, lateral offset, and width. The roadside slopes varied in length, slope rate, drop height, lateral offset, and width. The high frequency, high severity, and small lateral offset away from the roadway edge to culvert openings and roadside slopes made them prime candidates for consideration in an RSAP analysis to evaluate the cost-effectiveness of various safety treatments.

6.3 Barrier Selection

The existing barriers were selected for RSAP analysis based on the number of specific systems documented in the field, the condition of each system, and the ability to model the various systems in RSAP. The various barrier systems documented in the field investigation were W-beam guardrail, cable guardrail, flat-panel guardrail, modified W-beam guardrail, and roadside concrete barriers. Many of the documented systems provided little or no vehicle containment, thus allowing a high possibility of penetrating the existing barrier and interacting with the hazard as well. Thus, the best practice may be to remove these barriers (cable, flat-panel, and the concrete post and rail systems) and replace them with a crashworthy system meeting current design and safety guidelines.

Cable barriers are not a predefined feature in RSAP. They are assumed to have the same severity and containment level as a standard W-beam guardrail system. The existing cable barrier systems had slack cables, kinks, faulty transitions, strong-posts, non-standard cable brackets, and other deviations from a standard crashworthy, cable barrier system. No cable barrier systems had crashworthy terminal ends. The existing cable barriers would provide very little containment and redirection for an errant vehicle due to the slack cable segments, only one or two cable wire ropes, and lack of anchorage at many of the ends. Thus, cable barriers were not selected for evaluation in RSAP; since, cable barriers are modeled in a similar manner to that of W-beam guardrails. In addition, extensive deviations from standard practice were found in these cable barrier systems. Thus, the existing cable barrier systems should be considered for removal or replacement as no further RSAP analysis was completed. However, designers can utilize the barrier selection guidelines developed herein to determine the proper treatment of these special cases.

Likewise, flat-panel and concrete post and rail barriers found in the field investigation have become obsolete. Thus, these barriers could not be upgraded but instead must be removed. However, just like the obsolete cable barriers, designers can utilize the barrier selection guidelines developed herein to determine the proper treatment of these cases.

Strong-post, W-beam guardrail systems were the most common documented barrier system. Most of these systems had the ability to contain and redirect an errant vehicle, and therefore provided safety and societal some benefit to motorists. Due to the common occurrence of the strong-post, W-beam guardrail system and the modeling ability in RSAP, W-beam guardrail systems were ideal for this investigation. Additionally, the older versions of modified W-beam and channel rail systems were of similar conditions and appeared to provide similar strengths and capacities. Thus, modeling recommendations for the W-beam analysis would apply to these systems as well.

7 W-BEAM GUARDRAIL CONTAINMENT LEVEL – PERFORMANCE LIMITS

7.1 Problem

As stated previously, a major concern for existing W-beam guardrail systems is the top rail mounting height. An insufficient top rail height can allow vehicles to climb, override, or penetrate a guardrail system. These behaviors pose a major concern; since, a guardrail's primary function is to shield those hazards located behind them. Thus, guardrail height was an important parameter to model and consider in the RSAP analysis. There are two means of raising the guardrail height: (1) replace the barrier with a current standard height guardrail or (2) reset the rail to the original design height (if the barrier presented other deviations from the current standard, raising the rail may not be an option). Thus, replacement was the only option considered.

Determining guardrail heights to examine in RSAP was the first step of this analysis. The chosen heights should be representative of model the guardrail installations found in the field which can still redirect errant vehicles. After evaluating existing conditions encountered during the field investigation, three guardrail heights - 27 in. (686 mm), 25 in. (635 mm), and 22 in. (559 mm) - were selected for further investigation and evaluation in RSAP.

7.2 Low Rail Height Modeling Options in RSAP

The next step was to determine how to model different guardrail heights in RSAP. Options included changing the defined mounting height, severity index, and containment limit. The containment limit is defined as the maximum impact severity (IS) that a barrier can withstand without allowing an errant vehicle to penetrate or override the barrier.

RSAP uses barrier mounting heights to predict rollovers associated with heavy trucks. All other vehicles are unaffected by the change in the guardrail height. Thus, changing the defined mounting height in RSAP would not accurately model the performance of the barriers found in the field investigation.

Changing the severity index for each guardrail height could make lower guardrails more severe in an impact event, representing, for example, a higher potential for override or rollover. However, the research team could not obtain any data that would objectively measure the change in barrier performance associated with a low rail height.

Changing the containment limit based on vehicle type could accurately model existing barriers with low guardrail top mounting height. However, accurately identifying the effect of guardrail height versus vehicle size would be insurmountable.

The final option was to change the containment limit of the guardrail based on different guardrail heights alone. This option would not consider the full variation in vehicle properties found in the vehicle feet. This would require a short, yet complete, literature review of full-scale W-beam crash tests on different guardrail heights, and the results of this review would need to be correctly implemented into RSAP. It was found that changing the containment limit of guardrail with different rail heights would be the best means of modeling the 27-in. (686-mm), 25-in. (635-mm), and 22-in. (559-mm) guardrail heights in RSAP. The defined guardrail heights would also be changed to simulate rollover of the heavy truck vehicles.

7.3 Containment Limit Calculation

As stated previously, the containment limit is the maximum kinetic energy that a guardrail system can withstand during the successful containment and/or redirection of an impacting vehicle. This value is then compared to the impact severity (IS). The IS value is a portion of the kinetic energy of the impacting vehicle which is calculated by taking the lateral velocity vector squared and multiplying it one-half and the mass of the vehicle, as shown in Equation 2. Any vehicle impact condition with an IS value greater than the set containment limit has the potential to penetrate/override the defined barrier system.

$$IS = \frac{1}{2} * m(V * sin\theta)^2 \qquad (2)$$

where,

IS = Impact Severity (ft-lbf, Joules)
m = Mass of impacting vehicle (lbm, kg)
V = Velocity of impacting vehicle (ft/s, m/s)
θ = Angle of encroachment (deg)

7.4 Existing Test Review

To determine values of the containment limit for the three guardrail heights, a literature search was performed. These values were generated from previously tested and modeled W-beam guardrail crash tests. Finding W-beam guardrail systems which contained the vehicle and passed crash testing criteria with varying guardrail heights (preferably lower than standard) was vital to this analysis. The impact speed, vehicle type, and impact angle varied from these tests at different guardrail heights. From each test, the speed, impact angle, and the mass of the vehicle were used to determine the IS of the impact giving the containment limit for its respected guardrail height. Around 30 full-scale vehicle crash tests were considered. Only the highest IS value for its respective height was taken into consideration. No failed tests values were used.

7.5 Containment Level Results

The values for the selected guardrail test are shown in Table 13, and the resulting values used in RSAP are shown in Table 14. These values were then graphed in Figure 31. A best-fit linear regression line was created from the data points. From the slope of the best-fit line, containment limit values were found for the 27 in. (686 mm), 25 in. (635 mm), and 22 in. (559 mm) guardrail heights.

Table 13. Full-Cable W-beam Crash Test Information

Vehicle Type	Guardrail Height		Vehicle Weight		Angle	Speed		Containment Limit		Reference
	(in.)	(mm)	(lb)	(kg)	(deg.)	(mph)	(km/h)	(ft-lbf)	(Joules)	
2000P[1]	31	787	4,441	2,014	36.7	65.0	104.7	224,000	304,000	[53]
2000P[1]	27¾	705	4,577	2,076	25.5	63.1	101.5	113,000	153,000	[54]
2000P[1]	27	686	4,572	2,074	24.3	62.6	100.8	102,000	138,000	[55]
2270P[2]	25	635	5,004	2,270	25	43.5	70.0	57,000	77,000	Appendix B
Sedan[1]	24	610	4,570	2,073	25	59.0	95.0	95,000	129,000	[56]
2270P[2]	22	559	5,004	2,270	25	37.3	60.0	42,000	57,000	Appendix B

1 – Full-Scale Crash Test
2 – Crash Test Simulation

Table 14. Containment Limit Values Used in RSAP

Guardrail Height		Containment Limit	
(in.)	(mm)	(ft-lbf)	(Joules)
31	787	196,000	266,000
27	686	122,000	165,000
25	635	84,000	114,000
22	559	29,000	39,000

7.6 Discussion

It should be noted that two of the six points used to find the best fit line were determined by the use of simulation. A 2270P vehicle model impacted a W-beam guardrail at 22-in. (559-mm) and 25-in. (635-mm) rail heights with a 25-degree impact angle and varying speeds. The 25-in. (635-mm) guardrail height contained the impacting vehicle at 43.5 mph (70 km/h), thus resulting in a containment limit value of 57,000 ft-lbf (77,000 J). The 22-in. (559-mm) guardrail height failed to completely contain the vehicle at 43.5 mph (70 km/h), because the tire of the vehicle road on top of the rail element. This simulation was deemed to be “marginal,” so 37.3 mph (60 km/h) was used to determine the containment limit of 42,000 ft-lbf (56,000 J). The simulation results are shown in Appendix B.

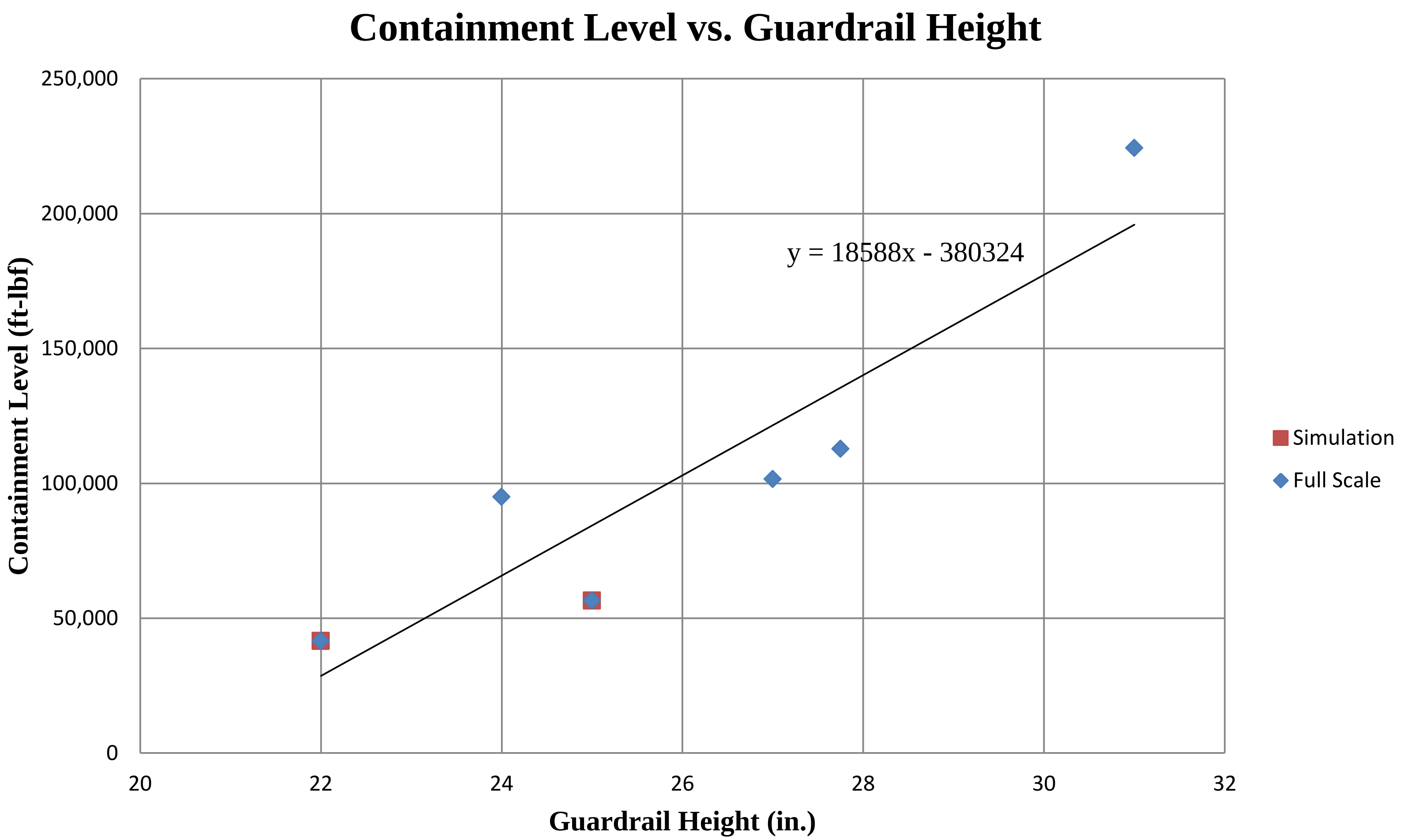


Figure 31. Containment Index from Selected Guardrail Tests

8 ANALYSIS OF EXISTING W-BEAM GUARDRAILS SHIELDING CULVERTS

8.1 Introduction

As noted previously, most W-beam guardrail systems that were documented in the field investigation were utilized to shield traffic from culvert openings. The existing W-beam guardrails utilized wood, concrete, or steel posts across the culvert. Most of the guardrail systems utilized wood posts which were placed in front of the culvert edge. W-beam guardrail systems, which utilize concrete posts, add the risk of a rigid hazard above the culvert. The steel posts and some wood posts were attached to the back side of the culvert with the use of two horizontal bolts embedded in the concrete head wall. The majority of these systems had low rail heights and blunt-end guardrail terminals. Therefore, it was deemed necessary to evaluate the cost-effectiveness of safety treatments for existing W-beam guardrails used to shield culvert openings.

8.2 Modeling of the Existing Guardrail Shielding Culverts

The existing W-beam guardrail and culvert systems were modeled in RSAP with a wide range of design parameters, as depicted in Table 15. First, a sensitivity analysis was performed in RSAP to determine if various parameters had a substantial effect on the accident cost. This process was completed by setting all roadway, culvert, and barrier variables constant in RSAP to represent the base condition. A rural, arterial, two-lane, undivided highway, ADT of 5,000 vpd, and a straight roadway segment were the roadway conditions modeled for the sensitivity analysis. Then, one parameter was changed to investigate if and how it affected the results. Several variables were subjected to a sensitivity analysis and were based on the project team’s discussion and engineering judgment. These design parameters and results are shown in Table 16. If the feature parameters had little difference to the baseline, only a few or one value was used for that variable in the final RSAP set. The last step in modeling the RSAP runs was a team discussion. The final W-beam constraints were determined based on the field investigation, sensitivity analysis, and engineering judgment.

Table 15. Variables Considered for W-Beams Shielding Culverts in RSAP

Features	Design Parameters
Roadway	ADT, Lane Width, Number of Lanes, Highway Type, Speed Limit, Shoulder Width
Barrier	System Length, Guardrail Height, Terminal Type, Lateral Offset
Culvert	Drop Height, Width, Length, Lateral Offset

Table 16. Culvert and W-beam Sensitivity Analysis - Parameters and Results

Design Parameter	Base Condition	Changed Condition	Estimated Annual Crash Costs (USD)	Percentage Change
Base	Base	none	$14,326	NA
End Treatment	Blunt-End	Turned-Down	$11,400	-20.4%
Terminal Flare	No Flare	1:25	$13,984	-2.4%
Culvert Length	30 ft (9.1 m)	10 ft (3.0 m)	$13,631	-4.9%
	30 ft (9.1 m)	50 ft (15.2 m)	$14,981	+4.6%
Culvert Drop Height	13 ft (4.0 m)	7 ft (2.1 m)	$14,258	-0.5%
	13 ft (4.0 m)	26 ft (7.9 m)	$14,362	+0.2%
Barrier Face Lateral Offset	4 ft (1.2 m)	2 ft (0.6 m)	$16,041	+12.0%
	4 ft (1.2 m)	7 ft (2.1 m)	$11,865	-17.2%
Guardrail Length of Need	221 ft (67.4 m)	190 ft (57.9 m)	$15,254	+6.5%
	221 ft (67.4 m)	250 ft (76.2 m)	$14,709	-2.7%

8.2.1 Length of Need Modeling

Based on the results from the sensitivity analysis, the guardrail length of need will not have a large impact on the RSAP results. So, guardrail length of need was modeled were to be in accordance with *Guardrail Run-Out Length Design Procedures Revisited* [57-58].

8.2.2 Guardrail Height Modeling

The guardrail heights that were modeled in RSAP to best evaluate the existing barrier systems were 31 in. (787 mm), 27 in. (686 mm), 25 in. (635 mm) and 22 in. (559 mm). The containment indices in RSAP were changed to 196,000 ft-lbf, 122,000 ft-lbf, 84,000 ft-lbf, and 29,000 ft-lbf (266,000 J, 165,000 J, 114,000 J, and 39,000 J), respectively for these heights, as described in Chapter 4.

8.2.3 End Terminal Modeling

Blunt-end and turned-down terminals were modeled in the B/C analysis for the existing guardrails. Although blunt-end terminals made up over 90 percent of the systems found in the field investigation, turned-down terminals were also considered to be an important feature for analysis with RSAP based on the sensitivity analysis. Both, turned-down and blunt-end terminals were predefined features in RSAP.

8.2.4 Guardrail Lateral Offset Modeling

The lateral offsets of the W-beam guardrail found in the field investigation varied from 2 ft (0.6 m) to 12 ft (3.7 m), measured from edge of traveled way to face of the barrier. Of the 42 W-beam lateral offsets documented, 36 were between 2 ft (0.6 m) and 7 ft (2.1 m). After the RSAP sensitivity analysis, 2-ft (0.6-m), 4-ft (1.2-m), and 7-ft (2.1-m) lateral offsets were chosen for guardrails shielding culverts. All guardrail parameters that were varied in the RSAP analysis are summarized in Table 17.

Table 17. W-Beam Parameters Shielding Culvert Hazards used in RSAP

<table>
<tr><th colspan="2">Guardrail Height</th><th colspan="2">Lateral Offset from Travelway</th><th colspan="2" rowspan="2">Tangent End Terminal</th></tr>
<tr><th>(in.)</th><th>(mm)</th><th>(ft)</th><th>(m)</th></tr>
<tr><td>22</td><td>559</td><td>2</td><td>0.6</td><td rowspan="3">Spoon</td><td rowspan="3">Turned-Down</td></tr>
<tr><td>25</td><td>635</td><td>4</td><td>1.2</td></tr>
<tr><td>27</td><td>686</td><td>7</td><td>2.1</td></tr>
</table>

8.2.5 Changes Made to Predefined W-Beam Feature in RSAP

8.2.5.1 Severity of Guardrail

As presented in NCHRP No. 665, RSAP default accident severities are too high [59]. In order to resolve this issue, NCHRP No. 665 developed an adjustment factor on guardrail impacts.

8.2.5.2 Repair Cost for TL-3 Barrier

In RSAP (Version 2003.04.01) [11], there is a predefined repair cost for all barrier types. An error exists in the guardrail input file (si7.dat) where the repair costs for the TL-3 barrier appeared to be off by an order of 10. This value was adjusted to eliminate this problem. Guardrail repair costs were found to have little influence on the total cost.

8.3 Culvert Modeling

Although guardrail evaluation is the primary focus of this research, an accurate representation of the culvert hazard is also important to determine when a barrier should be upgraded. Culvert geometries were determined based on information from the field investigation and the RSAP sensitivity analysis. To efficiently and accurately model culvert hazards in RSAP, the sizes and shapes of the culverts were matched to predefined features in RSAP.

The selected predefined intersecting slope drop-offs in RSAP were 7, 13, and 26 ft (2.1, 4.0, and 7.9 m) deep. Although a drop height less than 26 ft (7.9 m) would give a better representation of existing culverts found in the field investigation, it would have required interpolation between the predefined heights to generate representative impact severities. Since the actual severities of these drop heights are not specified in RSAP, the predefined heights provided in the RSAP module were utilized. After a review of the dimensions observed in the field investigation and completion of a sensitivity analysis, three culvert lengths, three lateral offsets, and three culvert drop heights were chosen for the RSAP analysis. A summary of the culvert modeling values is given in Table 18.

Table 18. Culvert Parameters Evaluated in RSAP

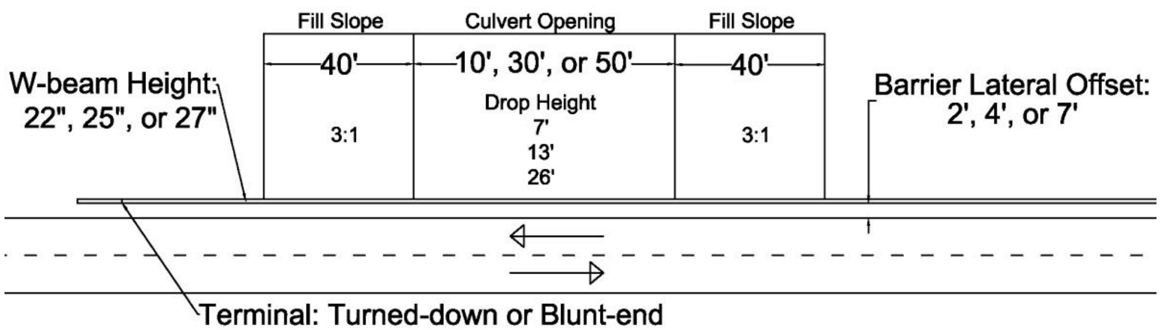
Culvert Length		Drop Height		Culvert Lateral Offset	
(ft)	(m)	(ft)	(m)	(ft)	(m)
10	3.0	7	2.1	3	0.9
30	9.1	13	4.0	5	1.5
50	15.2	26	7.9	8	2.4

8.4 Fill Slope Details

Fill slopes are often associated with culvert structures and can present risks to motorists as well, such as vehicle rollover. In the field investigation, fill slopes near culverts were no steeper 2:1, but most of these fill slopes were flatter than 3:1. For these reasons, only a fill slope of 3:1 was modeled in RSAP. The fill slopes were placed on both sides of the culvert opening. The widths of the fill slopes were set to the same 40 ft

(12.2 m), because it was found that changes did not greatly influence the results and simplified the RSAP model. A sketch of the existing W-beam guardrail shielding culvert openings modeled in RSAP is shown in Figure 32.

Figure 32. RSAP Parameter Model of Existing W-beam Guardrail Shielding Culvert Openings



8.5 Safety Treatment Options

The safety treatment options only included removal and/or upgrades to the existing barrier system without changes to the culvert and nearby sloped terrain. Thus, roadside grading, culvert extensions, and/or culvert grates were not considered in the RSAP analysis. Three treatment options that were considered are: (1) do nothing; (2) remove the existing barrier system; and (3) remove existing barrier system and install an approved guardrail system. These treatment options are discussed in greater detail in the following sections.

8.5.1 Do Nothing

The first safety treatment option was the "do nothing" option to the existing W-beam guardrail system. For this option, the existing barrier system would remain in place, despite any deviations from standard practice. Thus, the existing barrier system would remain if deemed suitable for shielding the hazard or if the cost associated with its removal and replacement exceeded the benefit, or reduction in accident costs.

8.5.2 Remove Existing Barrier System Only

The second safety treatment option was to remove the existing guardrail and end terminal systems. If the culvert drop-off has a large lateral offset away from the roadway edge and has a low drop height, an exposed culvert opening may be an acceptable alternative. As stated previously, protective guardrail systems should only be installed when crashes into the barrier are less severe than crashes into the roadside hazard. However, many of old, existing barrier systems were believed to pose greater risk than that provided by the hazards themselves. For these scenarios, system removal was recommended.

The removal of existing W-beam guardrail was estimated to cost $5.00 per linear foot ($16.40 per linear meter) [47]. Additional costs exist for traffic control as well as material and construction team mobilization. Thus, a contingency cost was used to cover all extra costs that were also considered for the removal of the existing W-beam guardrail. These supplementary costs of 10 percent, 7.5 percent, and 15 percent, respectively were added to the final cost of the barrier removal. Guardrail modeling details, costs, and sample calculations for removal of existing W-beams shielding culverts are shown in Appendix C. These costs only considered the removal of existing W-beam guardrail with steel or wooden posts. There should be extra consideration when concrete posts exist, which would increase the cost of removal.

Delineation of the culvert hazard is highly recommended if removal of the existing barrier system is the recommended treatment option. Delineation is a cost-effective means of reducing accident frequency. It should be noted that delineation cannot reduce the severity of vehicle run-off-the-road accidents, but it should reduce the frequency of them. Delineation has been proven to reduce the frequency of all vehicle accidents by 30 percent [60-61]. Because the benefit of delineation could not be quantified, it was not considered in the RSAP analysis.

8.5.3 Remove Existing Barrier System and Install Crashworthy W-Beam Guardrail

The third safety treatment option was to remove the existing guardrail and end terminal systems, which deviate from standard practice, and replace them with crashworthy W-beam guardrail and end treatment systems that meet current impact safety standards. This alternative would be implemented when a barrier system, including guardrail end terminals, is needed to shield a culvert opening. The new guardrail and end terminal systems were modeled with the same width, length, and lateral offset as the existing barriers, with the only differences being the 31-in. (787-mm) top-rail height and two crashworthy end terminals. The containment index of 196,000 ft-lbf (266,000 J) for a 31-in. (787-mm) tall guardrail was incorporated in RSAP, as described in Chapter 7.

Two different W-beam guardrail systems were considered for replacing the existing barrier on the culverts. The first system was an unsupported, W-beam guardrail system known as the MGS Long Span [33, 62]. The MGS Long Span is a W-beam guardrail system used for the protection of low-fill culverts. This system utilizes a long unsupported span which allows the low-fill culverts to be free from guardrail attachments. The second option was installing a W-beam guardrail in front of the culvert.

This option would be available if the culvert headwall extended far enough from the roadway for a standard W-beam guardrail to be installed.

Two TL-3 SKT terminals were modeled for cost consideration of the replacement barrier terminals [34-35]. The length of a SKT terminal was 37.5 ft (11.4 m). The terminal length modeled in RSAP was 12.5 ft (3.8 m) because beyond this point, the terminal can redirect errant vehicles and contribute to the system's length-of-need.

The cost to install a TL-3 W-beam guardrail system was assumed to be $18.16 per linear foot ($59.58 per linear meter) [47]. This cost was multiplied by the total length of rail minus two 37.5-ft (11.4-m) SKT terminal segments. The cost to install a SKT terminal was estimated to be to be $2,100 for the 37.5 ft (11.4 m) guardrail length. The cost to remove the existing barrier must also be under consideration for this alternative. The traffic control, transportation, and contingency costs are the same as for the removal of the barrier system with 10, 7.5, and 15 percent of the total cost, respectively. Guardrail modeling details, costs, and sample calculations for replacing existing W-beams shielding culverts are shown in Appendix C.

8.6 RSAP Simulations and Results

There were 4,860 scenarios simulated for existing W-beam guardrail systems that were used to shield culvert hazards. The complete RSAP B/C tables for the recommendations of existing W-beam barriers shielding culverts are shown in Appendix D. As expected, for most of the 22-in. (559 -m) top-rail height systems, replacement was recommended, but for 27-in. (686-mm) top-rail height systems, replacement was less frequently recommended. Existing barrier systems utilizing turned-down terminals were less likely to be replaced than those with blunt-end terminals. W-beam guardrail with a

22-in. (559-mm) mounting height and ADT higher than 500 vpd called for guardrail systems to be replaced in most cases. When the ADT is lower than 1,000, 25-in. and 27-in. (635-mm and 686-mm) tall W-beam guardrail systems were not recommended for replacement in most instances. Existing W-beam guardrail systems found on curves were recommended to be removed or replaced in most cases due to the greater amount of impacts caused by the horizontal curvature of the roadway.

8.7 Discussion

While W-beam guardrail was the most commonly found barrier system in the field investigation, culverts were the most represented roadside hazard shielded by these existing W-beam guardrail systems. The documented culverts had drop heights over 14 ft (4.3 m) and were over 50 ft (15.2 m) in length. Culverts are used to move water perpendicularly under the roadway and mitigate erosion. To keep expenses low, culvert structures are constructed with the headwall close to the roadway edge. This generates a low lateral offset for the barrier shielding these culverts. If the barrier isn't properly designed, installed, and maintained, it could create a severe hazard close to the roadway. For these reasons, existing barriers with known deviations from standard practice also may create a hazardous condition.

Some of the culverts found in the field investigation were shielded with W-beam guardrail which utilized concrete posts that attached to the top of the concrete headwall. The concrete post system and rail systems were essentially rigid and would likely be hazardous fixed objects with increased risk to motorists when positioned at small lateral offsets away from the roadway edge. As noted previously, MwRSF researchers examined W-beam systems with concrete posts attached to rural culvert structures in a report titled, *Cost-Effective Safety Treatments Low-Volume Roads* [47]. From this study, it was determined that all concrete posts would be removed on roadways with ADTs in excess of 50 vpd. Note that, the traffic volumes modeled for this project were always greater than or equal to 500 vpd. Thus, deficient W-beam guardrail systems with concrete posts found on culverts should be removed and analyzed as an unprotected culvert opening. With this in mind, guardrail improvement recommendations will follow very closely to a culvert without an existing barrier, and the RDG can determine the best practice on whether to keep the hazard unshielded or to install a barrier which meets current design and safety standards. Again, it is recommended that at the very least, the concrete post system should be removed on these highway types. For these reasons, culvert rails with concrete posts were not considered in the final RSAP testing matrix.

Delineation should be considered in addition to all treatment options, especially if the existing barrier was removed and not replaced. Delineation can aid in reducing the frequency of run-off-road accidents but does not reduce accident severity unless an alerted driver slows down before an impacting event.

8.8 Limitations of Culvert Model

This research has many limitations due to the fact that it was not feasible or able to model and analyze all existing barrier systems and deviations from standard practice. This recommendation only included existing strong-post, W-beam guardrail systems. Cable, flat-panel, and concrete rails were not included in this analysis of existing barrier systems shielding culverts. These systems would be difficult to accuratelymodel in RSAP.

The W-beam guardrail systems in the analysis only included those with steel and wood posts. Concrete posts were not included in the analysis which would require extra evaluation. Concrete posts on top of culverts would require extra removal equipment beyond that need for steel and wood posts, which would add to the total cost to transport and time to remove.

Guardrail height and outdated terminals were the only deviations from standard practice modeled in the RSAP analysis. Although these deviations were the most prominent and most severe, there were many other conditions that were documented during the field investigation which were not evaluated in this study. These deviations include rail damage, damaged and missing posts and blockouts, and insufficient length of need.

The only functional class modeled in RSAP was rural arterial highways. However, other functional classes were documented but not evaluated.

The RSAP analysis recommendations were based on costs at the time of the research study. Injury, fatality, installation, material, and other costs will continue to increase over time. If one cost increases faster than others, it may change the results of the B/C analysis (i.e. if material and installation costs increase with injury and fatality costs remaining constant, it may be less likely to install a new barrier system).

There are two typical treatments for culverts not evaluated in this report: (1) installing a culvert grate or (2) extending the headwall. Culvert grates can be installed on typical culvert sizes and have been found to be passably traversable by errant vehicles [63]. Extending the culvert to a farther offset, such as outside the clear zone, is another treatment option. This alternative would require that fill material be easily obtainable so it could be constructed with little earthwork to be economically viable. This report focused on upgrading existing guardrail systems, so these two alternatives were not considered for this project, although they may be the best treatment options.

Culverts are either found on flat ground or on a sag section of the roadway where the water can flow through a valley. Vertical sag curves on the roadway may increase the severity for all roadside features located in them due to the increased speed caused by the downward acceleration of a vehicle. Sag segments were not considered in the RSAP analysis. Thus, conservative recommendations were made when treating an existing guardrail shielding a culvert in a sag segment.

The barrier lateral offsets were modeled as 2 ft, 4 ft, and 7 ft (0.6 m, 1.2 m, and 2.1 m). Although these offsets considered most of the systems found in the field investigation, there were also offsets found outside of this range. Systems with lateral offsets greater than 7 ft (2.1 m) were found in many instances, which go up to 12 ft (3.7 m). These systems would have different results but were not included in this analysis.

9 ANALYSIS OF EXISTING GUARDRAILS SHIELDING ROADSIDE SLOPES

9.1 Introduction

The existing W-beam guardrail systems that were documented in the field investigation were also found to shield various roadside slopes. Most of these roadside slopes were considered to be foreslopes or fill slopes. Once again, existing W-beam guardrail systems deviated from standard practice due to low rail heights and the use of blunt-end terminals. Therefore, it was necessary to determine the cost-effectiveness of treatments based on the existing W-beam guardrails that were used to shield foreslopes. As previously noted, the existing W-beam guardrails utilized either wood or steel posts.

9.2 Modeling of Existing Guardrail Shielding Slopes

The existing W-beam guardrail and slope hazard were modeled in RSAP with a wide range of design parameters, as depicted in Table 19. The existing W-beam guardrail system and hazard had to be modeled to demonstrate a wide range of typical guardrails that were used to shield slopes. First, a sensitivity analysis was performed in RSAP to determine if the various parameters had a substantial effect on the accident cost. This process was completed by setting all roadway, slope, and barrier variables constant in RSAP to represent the base condition. A rural, arterial, two-lane, undivided highway, ADT of 5,000 vpd, and a straight roadway segment were the roadway conditions modeled for the sensitivity analysis. Then, one parameter was changed to investigate if and how it affected the results. Several variables were subjected to a sensitivity analysis and were based on the project team's discussion and engineering judgment. These design parameters and results are shown in Table 20. If the feature parameters had little difference to the baseline, only a few or one value was used for that variable in the final RSAP set.

Table 19. Variables Considered for W-Beams Shielding Slopes in RSAP

Feature	Design Parameters
Roadway	ADT, Lane Width, Number of Lanes, Highway Type, Speed Limit, Shoulder Width
Barrier	Length of Need, Guardrail Height, Terminal Type, Lateral Offset
Slope	Slope Rate, Drop Height, Width, Length, Lateral Offset

Table 20. Slope and W-beam Sensitivity Analysis - Parameters and Results

Design Parameter	Base	Change	Estimated Annual Crash Costs (USD)	Percentage Change
Base	Base	NA	$14,958	NA
End Treatment	Blunt-End	Turned-Down	$11,497	-23.1%
Terminal Flare	No Flare	1:25	$15,577	+4.1%
Slope Drop Height	13 ft (4.0 m)	7 ft (2.1 m)	$13,585	-9.2%
	13 ft (4.0 m)	20 ft (6.1 m)	$15,398	+2.9%
Slope Length	350 ft (106.7 m)	150 ft (45.7 m)	$12,723	-14.9%
	350 ft (106.7 m)	650 ft (198.1 m)	$18,556	+24.1%
Lateral Barrier Offset	4 ft (1.2 m)	2 ft (0.6 m)	$16,735	+11.9%
	4 ft (1.2 m)	7 ft (2.1 m)	$12,338	-17.5%
Guardrail Length of Need	221 ft (67.4 m)	190 ft (57.9 m)	$14,519	-2.9%
	221 ft (67.4 m)	250 (76.2 m)	$14,843	-0.8%

Modeling existing W-beam guardrail systems was determined by finding a set of parameters which best reflected what was found in the field investigation. Parameters which needed to be considered in modeling existing W-beam guardrail systems were guardrail length of need, rail height, terminal type, and lateral offset. W-beam guardrail shielding slopes had the same parameters that were determined for culverts in Section

8.2. Length of need, guardrail height, barrier offset, and terminal type were all modeled with the same values as used forculverts and are shown in Table 21

Table 21. W-Beam Parameters Shielding Slope Hazards used in RSAP

Guardrail Height		Lateral Offset from Travelway		Tangent End Terminal	
(in.)	(mm)	(ft)	(m)		
22	559	2	0.6	Spoon	Turned-Down
25	635	4	1.2		
27	686	7	2.1		

9.3 Slope Modeling

Although guardrail evaluation is the primary focus of this research, accurate modeling of the slope hazard is also important to depict the nature of what an existing barrier is shielding. Slope geometries were determined based on information from the field investigation, an RSAP sensitivity analysis, and a team discussion. To efficiently and accurately model the slopes in RSAP, the slope geometries were matched to predefined foreslopes in RSAP.

In RSAP, the Severity Index (SI) of the slopes was based on a survey of highway safety officials to rank the severity of accidents on a scale of 1 to 10. The predefined SI values for foreslopes in RSAP are believed to have a bias toward high-speed impacts [11]. As a result, the SI values were overestimated. A previous study by MwRSF developed new SI values for slopes based on actual accident data [45-46]. These values were implemented in the RSAP runs for this study.

Slopes were modeled using the dimensions observed in the field investigation, sensitivity analysis, and group discussion. Ultimately, three slope rates, three slope lengths, three slope drop heights, and three lateral offsets were chosen for the RSAP analysis. A summary of the slope modeling values is shown in Table 22.

Table 22. Slope Parameters Evaluated in RSAP

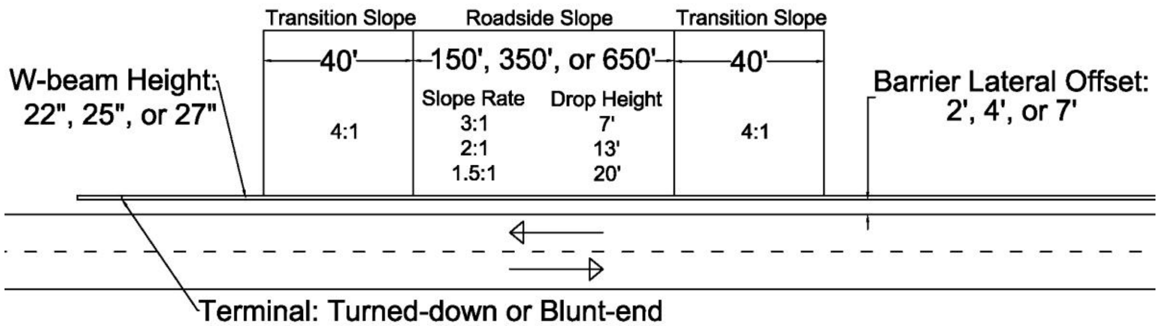
Slope Rate	Length		Drop Height		SBP Lateral Offset	
	(ft)	(m)	(ft)	(m)	(ft)	(m)
3:1	150	45.7	7	2.1	3	0.9
2:1	350	106.7	13	4.0	5	1.5
1.5:1	650	198.1	20	6.1	8	2.4

SBP – Slope Break Point

9.4 Transition Slope Modeling

A transition slope was considered to be a better model of existing slopes in the field investigation. This slope was modeled as a recoverable foreslope which was on the upstream and downstream end of the primary slope hazard in order to model a transition from a non-recoverable slope rate to flat ground, as seen on common highway slope hazards and in the field investigation. A 4:1 slope transition spanning 40 ft (12.2 m) on each end of the primary slope hazard was considered for the RSAP analysis. A sketch of the existing W-beam guardrail shielding slopes modeled in RSAP is shown in Figure 33.

Figure 33. RSAP Parameter Model of Existing W-beam Guardrail Shielding Roadside Slopes



9.5 Treatment Options

The safety treatment options only included removal and/or upgrades to the existing barrier system without changes to the existing slope. Thus, roadside grading was not considered in the analysis. If slope grading is found to be an applicable treatment options, the Roadside Grading Guidance [45-46] should be followed for specific roadside conditions. Three treatment options that were considered are: (1) do nothing; (2) remove the existing barrier system; and (3) remove existing barrier system and install an approved guardrail system. These treatment options are discussed in greater detail in the following sections.

9.5.1 Do Nothing

The first safety treatment was the “do nothing” option to the existing W-beam guardrail system. For this option, the existing barrier system would remain in place, despite any deviations from standard practice. Thus, the existing barrier system would remain if deemed suitable for shielding the hazard or if the cost associated with its removal and replacement exceeded the benefit, or reduction in accident costs.

9.5.2 Remove Existing Barrier System Only

The second safety treatment option was to remove the existing barrier system. As stated previously, most existing guardrail systems shielding slopes had low rail heights and blunt-end terminals, and in most cases will pose a greater hazard than the slope it is shielding. It is in these scenarios that this treatment option may be chosen.

The removal of existing W-beam guardrail was estimated to cost $5.00 per linear foot ($16.40 per linear meter) [47]. Additional costs exist for traffic control as well as material and construction team mobilization. Thus, a contingency cost which was used to cover all extra costs that were considered for the removal of the existing W-beam guardrail. These supplementary costs of 10 percent, 7.5 percent, and 15 percent, respectively, were added to the final cost of the barrier removal. Guardrail modeling details, costs, and sample calculations for removal of existing W-beams shielding roadside slopes are shown in Appendix E.

Delineation should be considered if removal of the existing barrier system is the recommended treatment option. Delineation is a cost-effective means of reducing accident frequency. It should be noted that delineation cannot reduce the severity of vehicle run-off-the-road accidents, but it should reduce the frequency of them. Delineation has been proven to reduce the frequency of all vehicle accidents by 30 percent [60-61]. Because the benefit of delineation could not be quantified it was not considered in the RSAP analysis. It should be noted that if the slope hazard is excessive in length, the use of delineation may become less cost-effective. Delineation should be highly considered for short, untreated slopes on roadways with horizontal or vertical curves.

9.5.3 Remove Existing Barrier System and Install Crashworthy W-Beam Guardrail

The third safety treatment option was to remove the existing guardrail and end terminal systems, which deviate from standard practice, and replace them with crashworthy W-beam guardrail and end treatment that systems meet current impact safety standards. This alternative would be implemented when a barrier system, including guardrail end terminals, is needed to shield a critical roadside slope. The new guardrail and end terminal systems were modeled with the same width and lateral offset as the existing barriers, with the only differences being the 31-in. (787-mm) top-rail height and two crashworthy end terminals. The containment index of 196,000 ft-lbf (266,000 J) for a 31-in. (787-mm) tall guardrail was incorporated into RSAP, as described in Chapter 7.

Two TL-3 SKT terminals were modeled for cost consideration of the replacement barrier terminals [34-35]. The length of a SKT terminal was 37.5 ft (11.4 m). The terminal length modeled in RSAP was 12.5 ft (3.8 m) because beyond this point, the terminal can redirect errant vehicles and contribute to the system's length-of-need.

The cost to install a TL-3 W-beam guardrail system was assumed to be $18.16 per linear foot ($59.58 per linear meter) [47]. This cost was multiplied by the total length of rail minus two 37.5-ft (11.4-m) SKT terminal segments. The cost to install a SKT terminal was estimated to be to be $2,100 for the 37.5 ft (11.4 m) guardrail length. The cost to remove the existing barrier must also be under consideration for this alternative. The traffic control, transportation, and contingency costs are 10, 7.5, and 15 percent of the total cost, respectively. Guardrail modeling details, costs, and sample calculations for replacing existing W-beams shielding slopes are shown in Appendix E.

9.6 RSAP Simulations and Results

There were 14,580 scenarios simulated for existing W-beam guardrail systems that were used to shield slopes. The complete RSAP B/C tables for the recommendations of existing W-beam barriers shielding slopes are shown in Appendix F. As expected, most of the 22-in. (559-mm) top-rail height systems are recommended for removal and replacement with fewer 27-in. (686-mm) top-rail heights needing replacement. Existing barrier systems utilizing turned-down terminals were less likely to be replaced than those with blunt-end treatments. The 25-in. and 27-in. (635-mm and 686-mm) tall W-beam guardrail systems only need replacement when the ADT is higher than 1,000 vpd in most cases. Roadside slopes that are 3:1 or flatter and configured with low drop heights were usually recommended for removal. Existing W-beam guardrail systems found on curves were recommended to be removed or replaced in most cases due to the greater amount of impacts caused by the horizontal curvature of the roadway.

9.7 Discussion

Slopes hazards are found on virtually all high-speed roadways and are often a severe hazard. They must be properly evaluated and considered for guardrail implementation in accordance with the RDG. Many existing barriers found on current highways that shield slopes are more severe than the slope they are shielding. These systems were documented and evaluated by RSAP to make recommendations for treatment. Guardrail implementation was recommended for most slopes between a 1.5 and 2:1. For the 3:1 slopes, slope rate, many guardrails were recommended for removal.

Delineation should be considered in addition to all treatment options, especially if the existing barrier is removed and not replaced. Delineation can aid in reducing the number and speed of impacts. It should be repeated that delineation can reduce the frequency of run-off-road accidents but does not reduce the severity of the accident unless it alerts the driver to slow down before the impacting event.

9.8 Limitations of the Slope Model

The slope model used in RSAP is a simplified with a standard 4:1 transition slope to the critical slope of 3:1, 2:1, and 1.5:1. This does not truly model the existing slopes which would have more of a transition zone. This simplified method was still found to accurately model the existing slopes with a less intricate RSAP model.

This version of RSAP does not consider the driver behavior on slopes. Drivers are more likely to attempt a corrective maneuver when the vehicle is encroaching on a foreslope than they are to continue in a straight line (which RSAP models). This corrective maneuver would increase the propensity for rollover; however, RSAP does not incorporate rollover into the calculation of the average severity index of a foreslope. Rollovers on foreslopes are incorporated by adding to the SI values of foreslopes instead of determining an actual probability of rollover [46, 50].

10 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Summary

The primary function of a guardrail is to prevent errant vehicles from impacting a roadside hazard or encroaching into a hazardous area. Guardrails are intended to shield a more severe hazard (based on judgment), yet many fatalities and serious injuries have resulted from vehicles impacting these safety devices. Many severe and fatal crashes may be caused by outdated guardrail installations that did not satisfy the prior and/or current safety performance standards. Existing guardrail installations can be found to be substandard in many ways, such as non-standard barrier types, antiquated end treatments, low rail heights, improper installations, variable post spacing, and inadequate lengths of need.

The objective of this research study was to develop guidelines for upgrading existing guardrail installations that have deviations from standard practice. Common deviations from standard practice include non-standard barrier types, antiquated end treatments, low rail heights, improper installations, and inadequate lengths-of-need. There existed a need for an economic analysis to determine the best safety treatment for existing W-beam barriers with deviations from standard practice.

A field investigation was performed on rural minor arterial highways in the state of Kansas. All system geometries, components, deviations from standard barriers, shielded hazards, and the roadway conditions were documented. Each field site and barrier installation was also thoroughly photographed to aid in the subsequent analysis. The types of barrier systems that were documented in the field investigation were: (1) strong-post, W-beam guardrails; (2) cable guardrails; (3) concrete barriers; (4) channel rails; and (5) modified versions of W-beam barrier systems. These barrier systems varied in length, height, hazard shielded, roadway offset, and condition pertaining to aged components, prior impacts, and installation practices.

Strong-post, W-beam guardrail systems were the most common documented barrier system and were the only barrier type selected for the RSAP analysis. Most of these systems had the ability to contain and redirect an errant and therefore provided some benefit to errant vehicles. The existing W-beam guardrail systems had many deviations from standard practice, but the most prominent were low-rail height and antiquated end treatments (i.e. blunt-end and turned-down systems). Additionally, the older versions of modified W-beam and channel rail systems were of similar conditions and appeared to provide similar strengths and capacities. Thus, modeling recommendations for the W-beam analysis would apply to these systems as well.

From the field investigation, culvert openings and roadside slopes were the most prominent hazards that were shielded by existing barrier systems. Both hazard types were found near the traveled way and are easily modeled using predefined features within RSAP. The culvert structures varied in length, drop height, lateral offset, and width. The roadside slopes varied in length, slope rate, drop height, lateral offset, and width. The high frequency, high severity, and small lateral offset away from the roadway edge to culvert openings and roadside slopes made them prime candidates for consideration in an RSAP analysis to evaluate the cost-effectiveness of various safety treatments.

10.2 Conclusions

10.2.1 Containment Level Study

The containment level study was conducted to better model existing W-beam guardrails with low rail heights. This study utilized previous crash tests and vehicle simulations to generate a graph of containment limit verses rail height. From this graph containment limit values were found for the 31-in. (787-mm), 27-in. (686-mm), 25-in. (635-mm), and 22-in. (559-mm) guardrail heights. The revised containment limits were determined whether a barrier is able to contain and redirect an errant vehicle with a low-rail height.

10.2.2 Existing W-beam Barriers Shielding Culverts

The existing guardrail, culvert openings, and roadway conditions were modeled from a field investigation conducted on Kansas highways. Three treatment options were examined during the analysis. The baseline option considered was to "do nothing" to the existing guardrail. This involved modeling the existing guardrail system and a culvert opening with different lengths, offsets, and drop heights. The first safety treatment alternative was to remove the existing guardrail. The removal of the existing barrier system was estimated to cost \$5.00 per linear foot (\$16.40 per linear meter). The estimated range of the total cost to remove the existing barrier system was between \$1,082.66 and \$3,173.43, which included traffic control, mobilization, and a contingency cost. The second safety treatment alternative was to remove the existing barrier system and install a barrier that meets current safety and design standards. In this case, the cost of installing a new W-beam guardrail systems was estimated to be \$18.16 per linear foot (\$59.58 per linear meter) with an end terminal installation cost of \$4,200 (for two SKT terminals). The estimated range of total costs to remove and install a new barrier system shielding culverts ranged between $8,776.22 and $18,462.61, which included traffic control, mobilization, and contingency costs. The complete RSAP B/C tables for the recommendations of existing W-beam guardrail shielding culverts are shown in Appendix D.

10.2.3 Existing W-beam Guardrail Systems Shielding Roadside Slopes

The second analysis was performed to model and evaluate existing W-beam guardrails shielding slopes and determine the cost-effectiveness of treating these systems with different safety alternatives. The W-beam guardrail system, roadside slope, and roadway conditions were modeled from a field investigation conducted on Kansas highways. Three treatment options were examined during the analysis. The baseline option was to “do nothing” to the existing barrier system. This involved modeling the existing guardrail system and a roadside slope with different slope rates, lengths, lateral offsets, and drop heights. The first safety treatment alternative was to remove the existing guardrail. The removal of the existing barrier system was estimated to cost $5.00 per linear foot ($16.40 per linear meter). The range of the total cost to remove the existing barrier system ranged between $2,076.15 and $7,312.99, which included traffic control, mobilization, and contingency costs. The second safety treatment alternative was to remove the existing barrier system and install a barrier that meets current safety and design standards. In this case, the cost of installing a new W-beam guardrail system was estimated to be $18.16 per linear foot ($59.58 per linear meter) with end terminal installation cost of $4,200 (for two SKT terminals). The range of the total cost to remove and install a W-beam guardrail system which meets all current standards ranged between

$13,379.01 and $37,510.31, which included traffic control, mobilization, and contingency costs. The complete RSAP B/C tables for the recommendations of existing W-beam guardrail shielding slopes are shown in Appendix F.

10.3 Recommendations

10.3.1 Existing Cable Barriers

Out of the 68 barrier systems that were documented in the field investigation, 9 were low-tension cable barrier systems. Most cables had kinks, slack (non-tensioned) spans, concrete posts, antiquated end treatments, and rusted components. The concrete posts will present blunt hazards to motorists, if impacted. The end sections of the existing barrier systems had two major concerns. First, they did not have sufficient anchorage to produce enough strength on the ends of the cable systems to redirect an errant vehicle. Second, the end posts were exposed to errant vehicles, presenting a blunt-end hazard. Missing posts were also found in some of the systems. The use of only 1-cable and 2-cable systems will pose a risk to motorists if the barrier is un able to safely contain or redirect a vehicle. The existing cable barriers found in the field investigation had very little, if any, containment capacity for capturing an errant vehicle due to the slack cable segments, only 1 or 2 cables, and lack of end anchorage at many of the end terminals. Cable barriers were not selected to be evaluated in RSAP, because they are not a predefined feature in RSAP and extensive deviations were found in these systems. Thus, the existing cable guardrail systems should be considered for removal or replacement. No further RSAP analysis was conducted for the cable barrier systems.

10.3.2 Flat-Panel Rail

Three of the 68 barrier systems that were documented consisted of steel, flat-panel barriers. This barrier utilized a steel panel rail and wood posts. The flat-panel rail found in the field investigation had a high potential to trip an errant vehicle because of the low top-rail mounting height of the rail element. The upstream and downstream end treatments of all flat-panel systems were blunt-ends with little or no anchorage. For these reasons, flat-panel barriers were not considered in the RSAP analysis. Removal of these barriers are recommend with a consideration of replacement with a new barrier that meets all current standards.

10.3.3 Existing Concrete Barriers

One concrete rail with concrete posts over a culvert was discovered in the field investigation. The barrier was not equipped with an end treatment. The concrete barrier found in the field investigation should be removed due to the fact it would act as a rigid blunt object which would most likely be more severe than any culvert it is shielding. Removal of this barrier is necessary on high-speed roadways. Replacement should be considered if the hazard is re-evaluated to be critical.

10.3.4 Existing W-Beam Type Guardrail

W-beam guardrails were the most common barrier systems that were documented in the field investigation, representing 45 of the 68 documented systems. Spoon (blunt-end) terminals were used on 40 of the W-beam guardrail systems, while the other five utilized turned-down terminals. The main deviations from standard practice found with W-beam barriers were low rail height and faulty end treatments. A number of systems had missing posts and blockouts. Other deviations from standard practice include faulty bridge rail connections, faulty end treatments, and system damage. Strong-post, W-beam guardrails were the only barriers considered for the RSAP analysis, because of their ability to be modeled and their high frequency in the field investigation. These barriers were found to shield a number of hazards which were predominantly culverts or slopes. Modified W-beam and channel rails were very comparable to the existing W-beam guardrails documented. For this reason, they were added to the analysis.

10.3.4.1 Shielding Culverts

There were 4,860 scenarios simulated for existing guardrails shielding culvert hazards. As expected, for most of the 22-in. (559-m) top-rail height systems, replacement was recommended, but for 27-in. (686-mm) top-rail height systems, replacement was less frequently recommended. Existing barrier systems utilizing turned-down terminals were less likely to be replaced than those with blunt-end terminals. W-beam guardrail with a 22-in. (559-mm) mounting height and ADT higher than 500 vpd called for guardrail systems to be replaced in most cases. When the ADT is lower than 1,000, 25-in. and 27-in. (635-mm and 686-mm) tall W-beam guardrail systems were not recommended for replacement in most instances. Existing W-beam found on curves were recommended to be removed or replaced in most cases due to the greater amount of impacts caused by the horizontal curvature of the roadway. The complete RSAP B/C tables for the recommendations of existing W-beam barriers shielding culverts are shown in Appendix D.

10.3.4.2 Shielding Slopes

There were 14,580 scenarios simulated for existing W-beam guardrail used to shield roadside slopes. As expected, most of the 22-in. (559-mm) top-rail height systems are recommended for removal and replacement with fewer 27-in. (686-mm) top-rail heights needing replacement. Existing barrier systems which utilized turned-down terminals were less likely to be replaced than those with blunt-end treatments. The 25-in. and 27-in. (635-mm and 686-mm) tall W-beam guardrail systems only need replacement when the ADT is higher than 1,000 vpd in most cases. Roadside slopes 3:1 slope rate or flatter with low drop heights were usually recommended for removal. Existing W-beam found on curves were recommended to be removed or replaced in most cases due to the greater amount of impacts caused by the horizontal curvature of the roadway. The complete RSAP B/C tables for the recommendations of existing W-beam barriers shielding slopes are shown in Appendix F.

11 LIMITATIONS AND FUTURE WORK

11.1 Limitations

This research has many limitations due to the fact that it was not possible to model and analyze all existing barrier systems and there deviations from standard practice. These RSAP recommendations herein included any barrier system besides existing strong-post W-beam guardrail systems. Cable, flat-panel, and concrete rails were not included in this analysis of existing barrier systems that were used to shielding culvert openings. These systems would be difficult to accurately model in RSAP.

The W-beam guardrail systems used in the RSAP analysis only included those barriers with steel and wooden posts. Concrete posts were not included in the analysis.. Concrete posts on top of culverts would require extra removal equipment as compared to to steel and wood posts, which would add to the total cost to transport and time to remove.

Guardrail height and outdated terminals were the only deviations from standard practice that were modeled in the RSAP analysis. Although these deviations were likely the most prominent and most severe, there were many other conditions that were documented during the field investigation which were not evaluated in this study such as: rail damage; damaged and missing posts and blockouts; and insufficient length of need.

The only functional class modeled in RSAP was rural minor arterial highways. Although, 90 percent of all roadways in the field investigation were minor arterial highways there were other functional classes documented but not evaluated.

The RSAP analysis recommendations were based on costs at the time of the research. Injury, fatality, installation, material, and other costs will continue to increase over time. This may alter the B/C analysis results in the future.

There are two typical treatments for culverts not evaluated in this report: (1) installing a culvert grate or (2) extending the headwall. Culvert grates can be installed on typical culvert sizes and have been found to be passably traversable by errant vehicles [63]. Extending the culvert to a farther offset, such as outside the clear zone, is another treatment option. This alternative would require that fill material is easily obtainable so it could be constructed with little earthwork to be economically feasible. This report focused on upgrading existing guardrail systems, so these two alternatives were not considered for this project, although they may be the best treatment practice.

Culverts are either found on flat ground or on a sag section of the roadway where the water can flow through a valley. Vertical sag curves on the roadway may increase the potential for vehicle enchroachments. This is due to the increase of speed caused by the downward acceleration of a vehicle. Sag segments were not considered in the RSAP analysis so conservative recommendations were made when treating an existing guardrail shielding a culvert in a sag segment.

The barrier lateral offsets were modeled as 2 ft, 4 ft, and 7 ft (0.6 m, 1.2 m, and 2.1 m). Although this models most of the systems found in the field investigation, there were also systems found outside of this range. Systems with offsets greater than 7 ft (2.1 m) were found in many instances which go up to 12 ft (3.7 m). These systems would have different results but were not included in this analysis.

This version of RSAP [11] does not considered the driver behavior on slopes. Drivers are more likely to attempt a corrective maneuver when the vehicle is encroaching on a foreslope than they are to continue in a straight line (which RSAP models). This corrective maneuver would increase the propensity for rollover; however, RSAP does not incorporate rollover into the calculation of the average severity index of a foreslope. Rollovers on foreslopes are incorporated by adding to the SI values of foreslopes instead of determining an actual probability of rollover [50, 46].

Over 60 percent of the W-beam barriers documented in the field investigation were found to be parallel to the roadway, making the end terminals tangent sections, leaving under 40 percent. This leaves the rest as flared terminal sections. Only tangent end terminals were modeled in RSAP to keep the testing matrix small and to make it possible to apply only one length of need to each roadway and hazard condition. While many of the documented systems had flared terminal sections, this was not considered for the RSAP analysis.

It should be repeated that although cable barriers were not considered for this analysis, they still could be a viable solution when replacement of the existing barrier system was recommended. In RSAP, there is no predefined cable barrier, so the W-beam and cable barriers are modeled the same. The only differences in modeling the two are the maximum defection and terminal types, which should also generate approximately the same severity for each type of barrier. Cable barriers should be considered on slopes when it is found to cost less and/or when a more forgiving barrier is needed for an errant vehicle. Additional deflection length must be considered when implementing cable barriers.

Soil grading as a treatment option for roadside foreslopes was not evaluated in this report. This treatment would lead to slope flattening (i.e., changing a 2:1 slope to a 6:1 slope). As the slope flattens, general vehicle instability and the potential for a rollover are also reduced. This treatment would require the transportation of soil material and possible purchase of land adjacent to the roadway. This report was focused on upgrading existing guardrail systems so roadside grading was not considered for this project although they may be the best treatment practice for certain cases. If slope grading is found to be an applicable treatment options, the Roadside Grading Guidance [45-46] should be followed for specific roadside conditions.

11.2 Recommendations for Future Work

The only evaluated functional class of roadway was rural minor arterial. In RSAP the functional class plays a major roll when determining vehicle speeds and encroachment probabilities. It would be beneficial to see the RSAP results on different functional classes of roadways.

The majority of barrier lateral offsets ranged from 2 ft to 7 ft (0.6 m to 2.1 m) in the field investigation. As a result lateral offsets greater than 7 ft (2.1 m) were not considered. RSAP encroachment predictions drop significantly as offsets increase. Thus, lateral offsets of 10 ft (3.0 m) could vary from the evaluated 7 ft (2.1 m). It would be beneficial to evaluate these RSAP models with larger lateral offsets.

The only recommended barrier upgrade in the RSAP analysis was a recommended 31 in. (787 mm) top-rail height. No upgrading by the addition of blockouts and raising the rail to the standard 27¾ in. (705 mm) were considered.

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13 APPENDICES

Appendix A. Field Investigation Form

FIELD INVESTIGATION DATA SHEET

Field Team Members:_______________________________ Date:____________________

I. DISTRICT NO.:__________________________

II. AREA NO.:______________________________

III. COUNTY NAME:________________________

IV. ROADWAY:

Highway No.: __________ Mile Marker:_________ Location:_________________(e/w or n/s)

No. Lanes: _______________________
Lane Width: _____________________
Shoulder Width: __________________
Median Width: ___________________

Grade: __________________________ (Flat, Shallow, Steep)
__________________________ (Up, Down, Sag, Crest)
Curve: __________________________ (None, Mild, Sharp)
__________________________ (Left, Right, NA)

Turn Lanes: ______________________ (Left, Right, Both, None)
Lane Markings: ___________________ (Paint, Thermoplastic)
Marking Condition: ________________ (Excellent, Good, Fair, Poor)
Roadway Lighting: ________________ (None, Spot, Continuous)
Speed Limit: _____________________

V. BARRIER SYSTEM:

A. Description/Identification and Measurements:

System Description: ____
(Strong post / weak post, rail type, etc.)

Barrier Length: ______________________(First post to last post)
Barrier Width: _______________________(Front rail face to back of post)

Lateral Barrier Offset:(Front rail face to edge of traveled way or lane)
US: ________________________
Mid: _______________________
DS: ________________________

1

Figure A-1. Field Investigation Form (1 of 4)

Approach Slope (rail face to shoulder edge) lateral offset is from roadway

Lateral Offset	2 ft	4 ft	6 ft	8 ft	10 ft	12 ft	Rail ___ ft
elev. US							
elev Mid							
elev. DS							

Backside Slope: Measured to 10 ft behind post or 30 ft from edge of roadway, whichever is greater.

Lateral Offset	Rail ___ ft	5 ft	___	10 ft	___	15 ft	___	20 ft	___	25 ft	___	30 ft
elev. US												
elev Mid												
elev. DS												

B. Rail:

Guardrail Element Type: ____________________
Guardrail Depth (vertical): US ____________ / Mid ____________ / DS ____________
Guardrail Width (horizontal): US ____________ / Mid ____________ / DS ____________
Guardrail Thickness: US ____________ / Mid ____________ / DS ____________

Guardrail Element Surface Condition: ________________________________
Guardrail Splices: _________________________(Type - Describe)
Guardrail Splice Bolts: __________________ (number and size)
Top Rail Mounting Height (High):* __________________ (*taken at face of rail)
Top Rail Mounting Height (Low): *__________________(*taken at face of rail)
Top Rail Mounting Height (High):** __________________(** relative to edge of roadway)
Top Rail Mounting Height (Low):** __________________(** relative to edge of roadway)

C. Posts:

No. of Posts: ____________________________
Post Spacing: ____________________________
Post Material: ____________________________
Post Shape: ____________________________
Post Size: ____________________________
Post Orientation: _________________________(Description, angle)*
* - Vertical, lean forward or backward, rotated upstream or downstream; degrees
Post Condition: ____
(Evaluate post condition 0-3" below grade at back side of at least 3 posts)

2

Figure A-2. Field Investigation Form (2 of 4)

D. Blockouts:

Blockout Material: ______________________________
Blockout Shape: ______________________________
Blockout Size: ______________________________
Blockout Orientation: ____________________________(Vertical, rotated US or DS)
Blockout Condition: ____________________________

E. Guardrail End Terminals:

Crashworthy Terminal (US End): __________________________________(Y or N; Describe)
Crashworthy Terminal (DS End): __________________________________(Y or N; Describe)

Terminal Geometry (US End): ____________________________(Flared, tangent, or parabolic)
Terminal Geometry (DS End): ____________________________(Flared, tangent, or parabolic)

Terminal Length (US End): ____________________________
Terminal Length (DS End): ____________________________
End Offset (US End): _________________________________
End Offset (DS End): _________________________________

Cable Anchorage (US End): _____________________________________(Y or N; Describe)
Cable Anchorage (DS End): _____________________________________(Y or N; Describe)

VI. HAZARD DESCRIPTION AND MEASUREMENTS:

Hazard Type: __________________________________
Hazard Width: _________________________________
Hazard Length: ________________________________
Distance from Rail Face to Front Face of Hazard: _____________________
US Guardrail End to Start of Hazard: _____________________________
DS Guardrail End to End of Hazard: ______________________________(Reverse traffic)

VII. OTHER DOCUMENTATION:

Site Photographs:_______________________________________(Photo No. X to Photo No. Y)*
* - Photographs from all vantage points for barrier system, hazard, and combinations thereof.

VIII. Additional Notes/Comments:
(damage to rail, missing elements / parts, incorrect installations, substandard systems)

3

Figure A-3. Field Investigation Form (3 of 4)

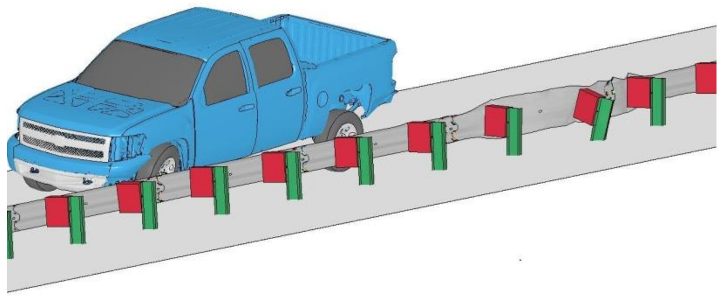
IX. Field Sketch (if necessary)

4

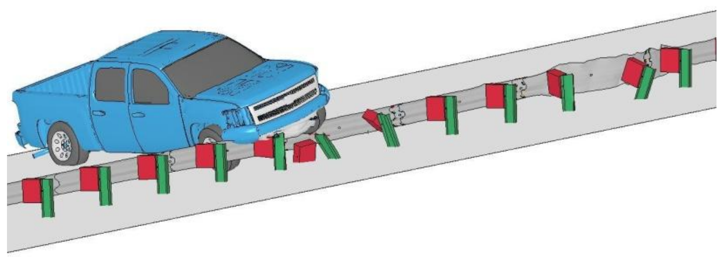
Figure A-4. Field Investigation Form (4 of 4)

Appendix B. LS-DYNA Guardrail Height Testing

37.3 mph
(60 km/h)



43.5 mph
(70 km/h)



62.1 mph
(100 km/h)

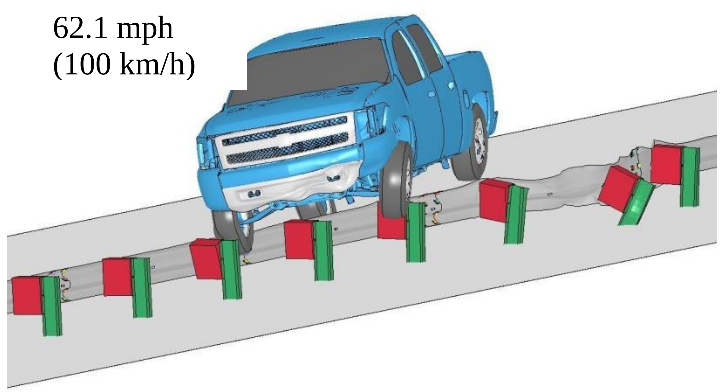


Figure B-1. Simulation Results for a 2270p Pickup Impacting 22-in. (589-mm) Rail Height.

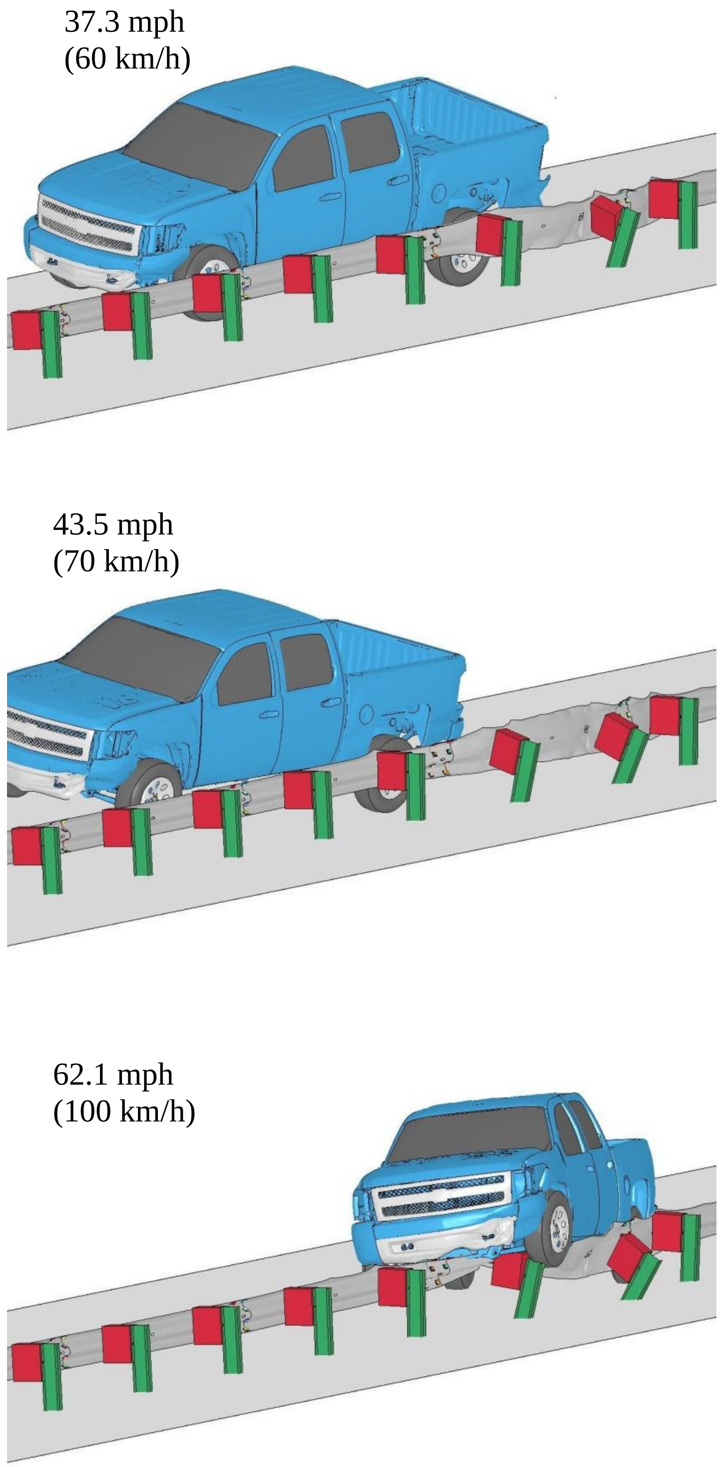


Figure B-2. Simulation Results for a 2270p Pickup Impacting 25-in. (635-mm) Rail Height.

Appendix C. Guardrail Modeling and Costs for Upgrading Existing W-beams Shielding Culvert Openings

Sample Calculations.

Table C-1. Interpolated Runout Lengths (L_R) [57-57]

L_R	Traffic Volume (ADT)							
	Under 1,000		1,000-5,000		5,000-10,000		Over 10,000	
Speed	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
55 mph (90 km/h)	150	45.7	165	50.3	190	57.9	235	71.6

Table C-2. Clear-zone Distances (L_C) Interpolated Values [7]

L_C	L_C Given Traffic Volume (ADT)							
	Under 750		750-1,500		1,500-6,000		Over 6,000	
Speed	(ft)	(m)	(ft)	(m)	(ft)	(m)	(ft)	(m)
55 mph (90 km/h)	13	4.0	17	5.2	21	6.4	23	7.0

First row of Table C-3:
Segment length = SGL = 3281 ft
ADT = 500 vpd
Slope Length = CL = 10 ft
Lateral Offset = OFF = 2 ft
Runout Length = LR = 150 ft (Table C-1)
Clear-zone distance = L_c = 13 ft (Table C-2)
Terminal Length = TL = 12.5 ft
Guardrail Removal Cost = GRRC = $5 per linear foot
TL-3 Terminal Cost = $2,100 (37 ft)
TL-3 Barrier Cost = $18.16 per linear foot
Added Costs:

- Traffic Control = 10%
- Mobilization = 7.5%
- Contingency = 15%

$$Culvert\ Starting\ Locatoin = \frac{SGL}{2} - \frac{CL}{2} = \frac{3281\ ft}{2} - \frac{10}{2} = 1635.4\ ft$$

$$Length\ of\ Need\ (LON) = \frac{L_c - OFF}{L_c/L_R} = \frac{13\ ft - 2\ ft}{13\ ft/150\ ft} = 126.9\ ft$$

$$W - beam\ Length = CL + LONx2 = 10\ ft + 126.9\ ft \times 2 = 263.8\ ft$$

$$Barrier\ Starting\ Location = Culvert\ Starting\ Locatoin - LON$$

$$= 1635.4\ ft - 126.9\ ft = 1508.5\ ft$$

$$Total\ Length\ of\ Barrier(TL) = CL + LON \times 2 + TLx2$$

$$= 10\ ft + 126.9\ ft \times 2 + 12.5 \times 2 = 288.8\ ft$$

$$Total\ Cost\ to\ Remove = TL \times GRRC \times\ (1 + 0.1 + .075 + 0.15)$$

$$= 288.8\ ft \times \frac{\$5}{lf} \times (1 + 0.1 + .075 + 0.15) = \$1{,}913.12$$

$$Total\ Cost\ to\ Remove\ \&\ Replace$$

$$= \Big(Total\ Cost\ to\ Remove + \big((TL - 37 \times 2) \times \$18.16 + \$2{,}100 \times 2\big)\Big)$$

$$\times (1 + 0.1 + .075 + 0.15) = \$12{,}623.68$$

Table C-3. Guardrail Shielding Culverts Modeling and Cost (English Units)

ADT	Culvert Length (ft)	Lateral Offset (ft)	Culvert Staring Location (ft)	Length of Need (ft)	W-beam Length (ft)	Barrier Starting Location (ft)	Terminal Length (ft)	Total Length of Barrier (ft)	Total Cost to Remove (USD)	Total Cost to Remove & Replace (USD)
500	10	2	1635.4	126.9	263.8	1508.5	12.5	288.8	$1,913.12	$12,623.68
		4	1635.4	103.8	217.7	1531.6	12.5	232.7	$1,541.19	$10,900.58
		7	1635.4	69.2	148.5	1566.2	12.5	163.5	$1,082.66	$8,776.22
	30	2	1625.4	126.9	283.8	1498.5	12.5	308.8	$2,045.58	$13,237.39
		4	1625.4	103.8	237.7	1521.6	12.5	232.7	$1,541.19	$10,900.58
		7	1625.4	69.2	168.5	1556.2	12.5	163.5	$1,082.66	$8,776.22
	50	2	1615.4	126.9	303.8	1488.5	12.5	303.8	$2,012.47	$13,083.96
		4	1615.4	103.8	257.7	1511.6	12.5	257.7	$1,706.77	$11,667.72
		7	1615.4	69.2	188.5	1546.2	12.5	188.5	$1,248.24	$9,543.35
1,000	10	2	1635.4	145.6	301.2	1489.8	12.5	301.2	$1,994.78	$13,002.04
		4	1635.4	126.2	262.4	1509.2	12.5	262.4	$1,737.64	$11,810.73
		7	1635.4	97.1	204.1	1538.4	12.5	204.1	$1,351.93	$10,023.76
	30	2	1625.4	145.6	321.2	1479.8	12.5	321.2	$2,127.25	$13,615.75
		4	1625.4	126.2	282.4	1499.2	12.5	282.4	$1,870.11	$12,424.44
		7	1625.4	97.1	224.1	1528.4	12.5	224.1	$1,484.40	$10,637.47
	50	2	1615.4	145.6	341.2	1469.8	12.5	341.2	$2,259.72	$14,229.45
		4	1615.4	126.2	302.4	1489.2	12.5	302.4	$2,002.58	$13,038.14
		7	1615.4	97.1	244.1	1518.4	12.5	244.1	$1,616.87	$11,251.17
5,000	10	2	1635.4	212.6	435.2	1422.8	12.5	435.2	$2,882.71	$17,115.76
		4	1635.4	190.2	390.5	1445.2	12.5	390.5	$2,586.24	$15,742.23
		7	1635.4	156.7	323.3	1478.8	12.5	323.3	$2,141.53	$13,681.93
	30	2	1625.4	212.6	455.2	1412.8	12.5	455.2	$3,015.18	$17,729.47
		4	1625.4	190.2	410.5	1435.2	12.5	410.5	$2,718.71	$16,355.94
		7	1625.4	156.7	343.3	1468.8	12.5	343.3	$2,274.00	$14,295.64
	50	2	1615.4	212.6	475.2	1402.8	12.5	475.2	$3,147.65	$18,343.18
		4	1615.4	190.2	430.5	1425.2	12.5	430.5	$2,851.17	$16,969.64
		7	1615.4	156.7	363.3	1458.8	12.5	363.3	$2,406.47	$14,909.34
10,000	10	2	1635.4	214.6	439.1	1420.9	12.5	439.1	$2,908.49	$17,235.20
		4	1635.4	194.1	398.3	1441.3	12.5	398.3	$2,637.80	$15,981.11
		7	1635.4	163.5	337.0	1471.9	12.5	337.0	$2,231.77	$14,099.96
	30	2	1625.4	214.6	459.1	1410.9	12.5	459.1	$3,040.96	$17,848.91
		4	1625.4	194.1	418.3	1431.3	12.5	418.3	$2,770.27	$16,594.81
		7	1625.4	163.5	357.0	1461.9	12.5	357.0	$2,364.23	$14,713.67
	50	2	1615.4	214.6	479.1	1400.9	12.5	479.1	$3,173.43	$18,462.61
		4	1615.4	194.1	438.3	1421.3	12.5	438.3	$2,902.73	$17,208.52
		7	1615.4	163.5	377.0	1451.9	12.5	377.0	$2,496.70	$15,327.38
25,000	10	2	1635.4	214.6	439.1	1420.9	12.5	439.1	$2,908.49	$17,235.20
		4	1635.4	194.1	398.3	1441.3	12.5	398.3	$2,637.80	$15,981.11
		7	1635.4	163.5	337.0	1471.9	12.5	337.0	$2,231.77	$14,099.96
	30	2	1625.4	214.6	459.1	1410.9	12.5	459.1	$3,040.96	$17,848.91
		4	1625.4	194.1	418.3	1431.3	12.5	418.3	$2,770.27	$16,594.81
		7	1625.4	163.5	357.0	1461.9	12.5	357.0	$2,364.23	$14,713.67
	50	2	1615.4	214.6	479.1	1400.9	12.5	479.1	$3,173.43	$18,462.61
		4	1615.4	194.1	438.3	1421.3	12.5	438.3	$2,902.73	$17,208.52
		7	1615.4	163.5	377.0	1451.9	12.5	377.0	$2,496.70	$15,327.38

Table C-4. Guardrail Shielding Culverts Modeling and Cost (Metric Units)

ADT	Culvert Length (m)	Lateral Offset (m)	Culvert Staring Location (m)	Length of Need (m)	W-beam Length (m)	Barrier Starting Location (m)	Terminal Length (m)	Total Length of Barrier (m)	Total Cost to Remove (USD)	Total Cost to Remove & Replace (USD)
500	3.0	0.6	498.5	38.7	80.4	459.8	3.8	88.0	$1,913.12	$12,623.68
		1.2	498.5	31.7	66.4	466.8	3.8	70.9	$1,541.19	$10,900.58
		2.1	498.5	21.1	45.3	477.4	3.8	49.8	$1,082.66	$8,776.22
	9.1	0.6	495.4	38.7	86.5	456.7	3.8	94.1	$2,045.58	$13,237.39
		1.2	495.4	31.7	72.4	463.8	3.8	70.9	$1,541.19	$10,900.58
		2.1	495.4	21.1	51.3	474.3	3.8	49.8	$1,082.66	$8,776.22
	15.2	0.6	492.4	38.7	92.6	453.7	3.8	92.6	$2,012.47	$13,083.96
		1.2	492.4	31.7	78.5	460.7	3.8	78.5	$1,706.77	$11,667.72
		2.1	492.4	21.1	57.4	471.3	3.8	57.4	$1,248.24	$9,543.35
1,000	3.0	0.6	498.5	44.4	91.8	454.1	3.8	91.8	$1,994.78	$13,002.04
		1.2	498.5	38.5	80.0	460.0	3.8	80.0	$1,737.64	$11,810.73
		2.1	498.5	29.6	62.2	468.9	3.8	62.2	$1,351.93	$10,023.76
	9.1	0.6	495.4	44.4	97.9	451.1	3.8	97.9	$2,127.25	$13,615.75
		1.2	495.4	38.5	86.1	457.0	3.8	86.1	$1,870.11	$12,424.44
		2.1	495.4	29.6	68.3	465.8	3.8	68.3	$1,484.40	$10,637.47
	15.2	0.6	492.4	44.4	104.0	448.0	3.8	104.0	$2,259.72	$14,229.45
		1.2	492.4	38.5	92.2	453.9	3.8	92.2	$2,002.58	$13,038.14
		2.1	492.4	29.6	74.4	462.8	3.8	74.4	$1,616.87	$11,251.17
5,000	3.0	0.6	498.5	64.8	132.7	433.7	3.8	132.7	$2,882.71	$17,115.76
		1.2	498.5	58.0	119.0	440.5	3.8	119.0	$2,586.24	$15,742.23
		2.1	498.5	47.8	98.6	450.7	3.8	98.6	$2,141.53	$13,681.93
	9.1	0.6	495.4	64.8	138.8	430.6	3.8	138.8	$3,015.18	$17,729.47
		1.2	495.4	58.0	125.1	437.4	3.8	125.1	$2,718.71	$16,355.94
		2.1	495.4	47.8	104.6	447.7	3.8	104.6	$2,274.00	$14,295.64
	15.2	0.6	492.4	64.8	144.9	427.6	3.8	144.9	$3,147.65	$18,343.18
		1.2	492.4	58.0	131.2	434.4	3.8	131.2	$2,851.17	$16,969.64
		2.1	492.4	47.8	110.7	444.6	3.8	110.7	$2,406.47	$14,909.34
10,000	3.0	0.6	498.5	65.4	133.8	433.1	3.8	133.8	$2,908.49	$17,235.20
		1.2	498.5	59.2	121.4	439.3	3.8	121.4	$2,637.80	$15,981.11
		2.1	498.5	49.8	102.7	448.6	3.8	102.7	$2,231.77	$14,099.96
	9.1	0.6	495.4	65.4	139.9	430.0	3.8	139.9	$3,040.96	$17,848.91
		1.2	495.4	59.2	127.5	436.3	3.8	127.5	$2,770.27	$16,594.81
		2.1	495.4	49.8	108.8	445.6	3.8	108.8	$2,364.23	$14,713.67
	15.2	0.6	492.4	65.4	146.0	427.0	3.8	146.0	$3,173.43	$18,462.61
		1.2	492.4	59.2	133.6	433.2	3.8	133.6	$2,902.73	$17,208.52
		2.1	492.4	49.8	114.9	442.6	3.8	114.9	$2,496.70	$15,327.38
25,000	3.0	0.6	498.5	65.4	133.8	433.1	3.8	133.8	$2,908.49	$17,235.20
		1.2	498.5	59.2	121.4	439.3	3.8	121.4	$2,637.80	$15,981.11
		2.1	498.5	49.8	102.7	448.6	3.8	102.7	$2,231.77	$14,099.96
	9.1	0.6	495.4	65.4	139.9	430.0	3.8	139.9	$3,040.96	$17,848.91
		1.2	495.4	59.2	127.5	436.3	3.8	127.5	$2,770.27	$16,594.81
		2.1	495.4	49.8	108.8	445.6	3.8	108.8	$2,364.23	$14,713.67
	15.2	0.6	492.4	65.4	146.0	427.0	3.8	146.0	$3,173.43	$18,462.61
		1.2	492.4	59.2	133.6	433.2	3.8	133.6	$2,902.73	$17,208.52
		2.1	492.4	49.8	114.9	442.6	3.8	114.9	$2,496.70	$15,327.38

Appendix D. Guidelines for Existing W-beam Guardrail Shielding Culvert Openings

Table D-1. 22-in. Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=2:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-2. 22-in.Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=4:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-3. 22 in. Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=2:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-4. 22-in.Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=4:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-5. 25-in. Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=2:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-6. 25-in. Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=4:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-7. 25-in. Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=2:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

(white)	Do Nothing
(light grey)	Remove deficient system
(dark grey)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-8. 25-in. Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=4:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-9. 27-in. Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=2:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-10. 27-in. Tall W-beam Guardrail with Blunt-End Terminal Shielding Culvert (B/C=4:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-11. 27-in. Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=2:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 2:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
	(ft)	(m)		2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table D-12. 27-in. Tall W-beam Guardrail with Turned-Down Terminal Shielding Culvert (B/C=4:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Culvert (B/C 4:1)												
Horiz. Curve	Drop Height		ADT	10 ft [3 m] Culvert Length Along Road			30 ft [9 m] Culvert Length Along Road			50 ft (15 m] Culvert Length Along Road		
				2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset	2 ft [0.6 m] Offset	4 ft [0.6 m] Offset	7 ft [2.1 m] Offset
	(ft)	(m)										
Straight Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									
5° Curved Segment	7	2.1	500									
			1,000									
			5,000									
			10,000									
			25,000									
	13	4.0	500									
			1,000									
			5,000									
			10,000									
			25,000									
	26	7.9	500									
			1,000									
			5,000									
			10,000									
			25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" Tall W-beam Guardrail with accptable end treatment

Appendix E. Guardrail Modeling and Costs for Upgrading Existing W-beams Shielding Slopes

Sample Calculations.

First row of Table E-1:
Segment length = SGL = 3281 ft
ADT = 500 vpd
Slope Length = SL = 150 ft
Lateral Offset = OFF = 2 ft
Runout Length = LR = 150 ft (Table C-1)
Clear-zone distance = L_c = 13 ft (Table C-2)
Terminal Length = TL = 12.5 ft
Guardrail Removal Cost = GRRC = $5 per linear foot
TL-3 Terminal Cost = $2,100 (37 ft)
TL-3 Barrier Cost = $18.16 per linear foot
Added Costs:

- Traffic Control = 10%
- Mobilization = 7.5%
- Contingency = 15%

$$Slope\ Starting\ Locatoin = \frac{SGL}{2} - \frac{SL}{2} = \frac{3281\ ft}{2} - \frac{150}{2} = 1565.4\ ft$$

$$Length\ of\ Need\ (LON) = \frac{L_c - OFF}{L_c/L_R} = \frac{13\ ft - 2\ ft}{13\ ft/150\ ft} = 126.9\ ft$$

$$W - beam\ Length = SL + LONx2 = 150\ ft + 126.9\ ft \times 2 = 403.8\ ft$$

$$Barrier\ Starting\ Location = Slope\ Starting\ Locatoin - LON$$

$$= 1565.4\ ft - 126.9\ ft = 1438.5\ ft$$

$$Total\ Length\ of\ Barrier(TL) = SL + LON \times 2 + TLx2$$

$$= 150\ ft + 126.9\ ft \times 2 + 12.5 \times 2 = 428.8\ ft$$

$$Total\ Cost\ to\ Remove = TL \times GRRC \times\ (1 + 0.1 + .075 + 0.15)$$

$$= 428.8\ ft \times \frac{\$5}{lf} \times (1 + 0.1 + .075 + 0.15) = \$2{,}840.38$$

$$Total\ Cost\ to\ Remove\ \&\ Replace$$

$$= \left(Total\ Cost\ to\ Remove + \left((TL - 37 \times 2) \times \$18.16 + \$2{,}100 \times 2\right)\right)$$

$$\times (1 + 0.1 + .075 + 0.15) = \$16{,}919.62$$

Table E-1. Guardrail Shielding Slope Modeling and Cost (English Units)

ADT	Slope Length (ft)	Lateral Offset (ft)	Slope Staring Location (ft)	Length of Need (ft)	W-beam Length (ft)	Barrier Starting Location (ft)	Terminal Length (ft)	Total Length of Barrier (ft)	Total Cost to Remove (USD)	Total Cost to Remove & Replace (USD)
500	150	2	1565.4	126.9	403.8	1438.5	12.5	428.8	$2,840.38	$16,919.62
		4	1565.4	103.8	207.7	1461.6	12.5	382.7	$2,534.69	$15,503.38
		7	1565.4	69.2	138.5	1496.2	12.5	313.5	$2,076.15	$13,379.01
	350	2	1465.4	126.9	603.8	1338.5	12.5	628.8	$4,165.04	$23,056.69
		4	1465.4	103.8	207.7	1361.6	12.5	582.7	$3,859.35	$21,640.44
		7	1465.4	69.2	138.5	1396.2	12.5	513.5	$3,400.81	$19,516.07
	650	2	1315.4	126.9	903.8	1188.5	12.5	928.8	$6,152.03	$32,262.28
		4	1315.4	103.8	207.7	1211.6	12.5	882.7	$5,846.34	$30,846.03
		7	1315.4	69.2	138.5	1246.2	12.5	813.5	$5,387.80	$28,721.66
1,000	150	2	1565.4	145.6	441.2	1419.8	12.5	466.2	$3,087.63	$18,065.12
		4	1565.4	126.2	252.4	1439.2	12.5	427.4	$2,830.49	$16,873.80
		7	1565.4	97.1	194.1	1468.4	12.5	369.1	$2,444.78	$15,086.84
	350	2	1465.4	145.6	641.2	1319.8	12.5	666.2	$4,412.29	$24,202.18
		4	1465.4	126.2	252.4	1339.2	12.5	627.4	$4,155.15	$23,010.87
		7	1465.4	97.1	194.1	1368.4	12.5	569.1	$3,769.44	$21,223.90
	650	2	1315.4	145.6	941.2	1169.8	12.5	966.2	$6,399.28	$33,407.77
		4	1315.4	126.2	252.4	1189.2	12.5	927.4	$6,142.14	$32,216.46
		7	1315.4	97.1	194.1	1218.4	12.5	869.1	$5,756.43	$30,429.49
5,000	150	2	1565.4	212.6	575.2	1352.8	12.5	600.2	$3,975.56	$22,178.84
		4	1565.4	190.2	380.5	1375.2	12.5	555.5	$3,679.09	$20,805.31
		7	1565.4	156.7	313.3	1408.8	12.5	488.3	$3,234.38	$18,745.01
	350	2	1465.4	212.6	775.2	1252.8	12.5	800.2	$5,300.22	$28,315.90
		4	1465.4	190.2	380.5	1275.2	12.5	755.5	$5,003.75	$26,942.37
		7	1465.4	156.7	313.3	1308.8	12.5	688.3	$4,559.04	$24,882.07
	650	2	1315.4	212.6	1075.2	1102.8	12.5	1100.2	$7,287.21	$37,397.63
		4	1315.4	190.2	380.5	1125.2	12.5	1055.5	$6,990.74	$36,101.85
		7	1315.4	156.7	313.3	1158.8	12.5	988.3	$6,546.03	$34,087.66
10,000	150	2	1565.4	214.6	579.1	1350.9	12.5	604.1	$4,001.34	$22,298.28
		4	1565.4	194.1	388.3	1371.3	12.5	563.3	$3,730.65	$21,044.18
		7	1565.4	163.5	327.0	1401.9	12.5	502.0	$3,324.61	$19,163.04
	350	2	1465.4	214.6	779.1	1250.9	12.5	804.1	$5,326.00	$28,435.34
		4	1465.4	194.1	388.3	1271.3	12.5	763.3	$5,055.31	$27,181.24
		7	1465.4	163.5	327.0	1301.9	12.5	702.0	$4,649.27	$25,300.10
	650	2	1315.4	214.6	1079.1	1100.9	12.5	1104.1	$7,312.99	$37,510.31
		4	1315.4	194.1	388.3	1121.3	12.5	1063.3	$7,042.30	$36,327.20
		7	1315.4	163.5	327.0	1151.9	12.5	1002.0	$6,636.26	$34,505.69
25,000	150	2	1565.4	214.6	579.1	1350.9	12.5	604.1	$4,001.34	$22,298.28
		4	1565.4	194.1	388.3	1371.3	12.5	563.3	$3,730.65	$21,044.18
		7	1565.4	163.5	327.0	1401.9	12.5	502.0	$3,324.61	$19,163.04
	350	2	1465.4	214.6	779.1	1250.9	12.5	804.1	$5,326.00	$28,435.34
		4	1465.4	194.1	388.3	1271.3	12.5	763.3	$5,055.31	$27,181.24
		7	1465.4	163.5	327.0	1301.9	12.5	702.0	$4,649.27	$25,300.10
	650	2	1315.4	214.6	1079.1	1100.9	12.5	1104.1	$7,312.99	$37,510.31
		4	1315.4	194.1	388.3	1121.3	12.5	1063.3	$7,042.30	$36,327.20
		7	1315.4	163.5	327.0	1151.9	12.5	1002.0	$6,636.26	$34,505.69

Table E-2. Guardrail Shielding Slope Modeling and Cost (Metric Units)

ADT	Slope Length (m)	Lateral Offset (m)	Slope Staring Location (m)	Length of Need (m)	W-beam Length (m)	Barrier Starting Location (m)	Terminal Length (m)	Total Lenght of Barrier (m)	Total Cost to Remove (USD)	Total Cost to Remove & Replace (USD)
500	45.7	0.6	477.1	38.7	123.1	438.5	3.8	130.7	$2,840.38	$16,919.62
		1.2	477.1	31.7	63.3	445.5	3.8	116.6	$2,534.69	$15,503.38
		2.1	477.1	21.1	42.2	456.0	3.8	95.5	$2,076.15	$13,379.01
	106.7	0.6	446.7	38.7	184.1	408.0	3.8	191.7	$4,165.04	$23,056.69
		1.2	446.7	31.7	63.3	415.0	3.8	177.6	$3,859.35	$21,640.44
		2.1	446.7	21.1	42.2	425.6	3.8	156.5	$3,400.81	$19,516.07
	198.1	0.6	400.9	38.7	275.5	362.3	3.8	283.1	$6,152.03	$32,262.28
		1.2	400.9	31.7	63.3	369.3	3.8	269.0	$5,846.34	$30,846.03
		2.1	400.9	21.1	42.2	379.8	3.8	247.9	$5,387.80	$28,721.66
1,000	45.7	0.6	477.1	44.4	134.5	432.8	3.8	142.1	$3,087.63	$18,065.12
		1.2	477.1	38.5	76.9	438.7	3.8	130.3	$2,830.49	$16,873.80
		2.1	477.1	29.6	59.2	447.6	3.8	112.5	$2,444.78	$15,086.84
	106.7	0.6	446.7	44.4	195.4	402.3	3.8	203.1	$4,412.29	$24,202.18
		1.2	446.7	38.5	76.9	408.2	3.8	191.2	$4,155.15	$23,010.87
		2.1	446.7	29.6	59.2	417.1	3.8	173.5	$3,769.44	$21,223.90
	198.1	0.6	400.9	44.4	286.9	356.6	3.8	294.5	$6,399.28	$33,407.77
		1.2	400.9	38.5	76.9	362.5	3.8	282.7	$6,142.14	$32,216.46
		2.1	400.9	29.6	59.2	371.4	3.8	264.9	$5,756.43	$30,429.49
5,000	45.7	0.6	477.1	64.8	175.3	412.3	3.8	183.0	$3,975.56	$22,178.84
		1.2	477.1	58.0	116.0	419.2	3.8	169.3	$3,679.09	$20,805.31
		2.1	477.1	47.8	95.5	429.4	3.8	148.8	$3,234.38	$18,745.01
	106.7	0.6	446.7	64.8	236.3	381.9	3.8	243.9	$5,300.22	$28,315.90
		1.2	446.7	58.0	116.0	388.7	3.8	230.3	$5,003.75	$26,942.37
		2.1	446.7	47.8	95.5	398.9	3.8	209.8	$4,559.04	$24,882.07
	198.1	0.6	400.9	64.8	327.7	336.1	3.8	335.4	$7,287.21	$37,397.63
		1.2	400.9	58.0	116.0	343.0	3.8	321.7	$6,990.74	$36,101.85
		2.1	400.9	47.8	95.5	353.2	3.8	301.2	$6,546.03	$34,087.66
10,000	45.7	0.6	477.1	65.4	176.5	411.7	3.8	184.1	$4,001.34	$22,298.28
		1.2	477.1	59.2	118.3	418.0	3.8	171.7	$3,730.65	$21,044.18
		2.1	477.1	49.8	99.7	427.3	3.8	153.0	$3,324.61	$19,163.04
	106.7	0.6	446.7	65.4	237.5	381.3	3.8	245.1	$5,326.00	$28,435.34
		1.2	446.7	59.2	118.3	387.5	3.8	232.6	$5,055.31	$27,181.24
		2.1	446.7	49.8	99.7	396.8	3.8	214.0	$4,649.27	$25,300.10
	198.1	0.6	400.9	65.4	328.9	335.5	3.8	336.5	$7,312.99	$37,510.31
		1.2	400.9	59.2	118.3	341.8	3.8	324.1	$7,042.30	$36,327.20
		2.1	400.9	49.8	99.7	351.1	3.8	305.4	$6,636.26	$34,505.69
25,000	45.7	0.6	477.1	65.4	176.5	411.7	3.8	184.1	$4,001.34	$22,298.28
		1.2	477.1	59.2	118.3	418.0	3.8	171.7	$3,730.65	$21,044.18
		2.1	477.1	49.8	99.7	427.3	3.8	153.0	$3,324.61	$19,163.04
	106.7	0.6	446.7	65.4	237.5	381.3	3.8	245.1	$5,326.00	$28,435.34
		1.2	446.7	59.2	118.3	387.5	3.8	232.6	$5,055.31	$27,181.24
		2.1	446.7	49.8	99.7	396.8	3.8	214.0	$4,649.27	$25,300.10
	198.1	0.6	400.9	65.4	328.9	335.5	3.8	336.5	$7,312.99	$37,510.31
		1.2	400.9	59.2	118.3	341.8	3.8	324.1	$7,042.30	$36,327.20
		2.1	400.9	49.8	99.7	351.1	3.8	305.4	$6,636.26	$34,505.69

Appendix F. Guidelines for Existing W-beam Shielding Slopes

Table F-1. 22-in.Tall W-beam with Blunt-End Shielding Slope (B/C=2:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

(white)	Do Nothing
(light grey)	Remove deficient system
(dark grey)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-2. 22-in.Tall W-beam with Blunt-End Shielding Slope (B/C=4:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-3. 22-in.Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=2:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-4. 22-in.Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=4:1)

22 in. (559 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Light	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
	4 ft [1.2 m]	500	Light	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
	7 ft [2.1 m]	500	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
13 ft [4.0 m]	2 ft [0.6 m]	500	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
	4 ft [1.2 m]	500	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
	7 ft [2.1 m]	500	Dark	Light	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
20 ft [6.1 m]	2 ft [0.6 m]	500	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
	4 ft [1.2 m]	500	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
	7 ft [2.1 m]	500	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		1,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		5,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		10,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light
		25,000	Dark	Dark	Light	Dark	Dark	Light	Dark	Dark	Light

White	Do Nothing
Light	Remove deficient system
Dark	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-5. 22-in.Tall W-beam with Turned-Down Shielding Slope (B/C=2:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Remove and install	Do Nothing	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
13 ft [4.0 m]	2 ft [0.6 m]	500	Remove and install	Do Nothing	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Remove and install	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
20 ft [6.1 m]	2 ft [0.6 m]	500	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Remove and install	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove
		5,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		10,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install
		25,000	Remove and install	Remove and install	Remove	Remove and install	Remove and install	Remove and install	Remove and install	Remove and install	Remove and install

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-6. 22-in.Tall W-beam with Turned-Down Shielding Slope (B/C=4:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-7. 22-in.Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=2:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-8. 22-in.Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=4:1)

22 in. (559 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-9. 25-in. Tall W-beam with Blunt-End Shielding Slope (B/C=2:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-10. 25-in. Tall W-beam with Blunt-End Shielding Slope (B/C=4:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-11. 25-in. Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=2:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-12. 25-in. Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=4:1)

25 in. (635 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-13. 25-in. Tall W-beam with Turned-Down Shielding Slope (B/C=2:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
13 ft [4.0 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Remove
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Do Nothing	Remove	Replace	Replace	Remove	Replace	Do Nothing	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
20 ft [6.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Do Nothing
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Replace	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Replace	Do Nothing	Do Nothing
		5,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		10,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
		25,000	Replace	Replace	Remove	Replace	Replace	Remove	Replace	Replace	Replace
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Replace	Replace	Remove	Replace	Replace	Replace	Replace	Replace	Replace
		10,000	Replace	Replace	Remove	Replace	Replace	Replace	Replace	Replace	Replace
		25,000	Replace	Replace	Remove	Replace	Replace	Replace	Replace	Replace	Replace

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-14. 25-in. Tall W-beam with Turned-Down Shielding Slope (B/C=4:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-15. 25-in. Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=2:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-16. 25-in. Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=4:1)

25 in. (635 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-17. 27-in. Tall W-beam with Blunt-End Shielding Slope (B/C=2:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Install	Install	Remove	Install	Install	Remove	Do Nothing	Do Nothing	Remove
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Install	Install	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Install	Install	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Remove
13 ft [4.0 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		1,000	Install	Install	Remove	Install	Install	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		1,000	Install	Install	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Install	Install	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
20 ft [6.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		1,000	Install	Install	Remove	Install	Install	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Do Nothing
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		1,000	Install	Install	Remove	Install	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		10,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install
		25,000	Install	Install	Remove	Install	Install	Remove	Install	Install	Install

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-18. 27-in. Tall W-beam with Blunt-End Shielding Slope (B/C=4:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
13 ft [4.0 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Remove
20 ft [6.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove & install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		1,000	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing	Do Nothing
		5,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Do Nothing
		10,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Do Nothing	Do Nothing	Do Nothing
		25,000	Remove & install	Remove & install	Remove	Remove & install	Remove & install	Remove	Remove & install	Do Nothing	Remove

Legend	
(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-19. 27-in. Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=2:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	4 ft [1.2 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Do Nothing	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
13 ft [4.0 m]	2 ft [0.6 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	4 ft [1.2 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
20 ft [6.1 m]	2 ft [0.6 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	4 ft [1.2 m]	500	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system	Do Nothing	Do Nothing	Remove deficient system
		1,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment
		5,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment
		10,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment
		25,000	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-20. 27-in. Tall W-beam with Blunt-End on Curve Shielding Slope (B/C=4:1)

27 in. (686 mm) W-beam with Blunt End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-21. 27-in. Tall W-beam with Turned-Down Shielding Slope (B/C=2:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	N	N	R	N	N	R	N	N	R
		1,000	N	N	R	N	N	R	N	N	R
		5,000	I	I	R	I	I	R	I	I	R
		10,000	I	I	R	I	I	R	I	I	R
		25,000	I	I	R	I	I	R	I	I	R
	4 ft [1.2 m]	500	N	N	R	N	N	R	N	N	R
		1,000	N	N	R	N	N	R	N	N	R
		5,000	I	I	R	I	I	R	I	I	R
		10,000	I	I	R	I	I	R	I	I	R
		25,000	I	I	R	I	I	R	I	I	R
	7 ft [2.1 m]	500	N	N	R	N	N	R	N	N	R
		1,000	N	N	R	N	N	R	N	N	R
		5,000	I	I	R	I	I	R	I	I	R
		10,000	I	I	R	I	I	R	I	I	R
		25,000	I	I	R	I	I	R	I	I	R
13 ft [4.0 m]	2 ft [0.6 m]	500	N	N	R	N	N	N	N	N	N
		1,000	N	N	R	N	N	R	N	N	N
		5,000	I	I	R	I	I	R	I	I	I
		10,000	I	I	R	I	I	R	I	I	I
		25,000	I	I	R	I	I	R	I	I	I
	4 ft [1.2 m]	500	N	N	R	N	N	N	N	N	N
		1,000	N	N	R	N	N	N	N	N	N
		5,000	I	I	R	I	I	I	I	I	I
		10,000	I	I	R	I	I	I	I	I	I
		25,000	I	I	R	I	I	I	I	I	I
	7 ft [2.1 m]	500	N	N	N	N	N	N	N	N	N
		1,000	N	N	R	N	N	N	N	N	N
		5,000	I	I	R	I	I	I	I	I	I
		10,000	I	I	R	I	I	I	I	I	I
		25,000	I	I	R	I	I	I	I	I	I
20 ft [6.1 m]	2 ft [0.6 m]	500	N	N	R	N	N	N	N	N	N
		1,000	N	N	R	N	N	N	N	N	N
		5,000	I	I	R	I	I	I	I	I	I
		10,000	I	I	R	I	I	I	I	I	I
		25,000	I	I	R	I	I	I	I	I	I
	4 ft [1.2 m]	500	N	N	R	N	N	N	N	N	N
		1,000	N	N	R	N	N	N	N	N	N
		5,000	I	I	R	I	I	I	I	I	I
		10,000	I	I	R	I	I	I	I	I	I
		25,000	I	I	R	I	I	I	I	I	I
	7 ft [2.1 m]	500	N	N	N	N	N	N	N	N	N
		1,000	N	N	R	N	N	N	N	N	N
		5,000	I	I	R	I	I	I	I	I	I
		10,000	I	I	R	I	I	I	I	I	I
		25,000	I	I	R	I	I	I	I	I	I

N	Do Nothing
R	Remove deficient system
I	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-22. 27-in. Tall W-beam with Turned-Down Shielding Slope (B/C=4:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Slope on Straight Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-23. 27-in. Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=2:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 2:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
13 ft [4.0 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
20 ft [6.1 m]	2 ft [0.6 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove
	4 ft [1.2 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
	7 ft [2.1 m]	500	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Remove	Do Nothing	Do Nothing	Do Nothing
		1,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		5,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		10,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install
		25,000	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove	Remove & Install	Remove & Install	Remove & Install

(white)	Do Nothing
(light gray)	Remove deficient system
(dark gray)	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment

Table F-24. 27-in. Tall W-beam with Turned-Down on Curve Shielding Slope (B/C=4:1)

27 in. (686 mm) W-beam with Turned Down End Terminal Shielding a Slope on 5° Curved Road Segment (B/C 4:1)											
Drop Height	Offset	ADT	150 ft [46 m] Slope Length			350 ft [107 m] Slope Length			650 ft [198 m] Slope Length		
			1.5:1	2:1	3:1	1.5:1	2:1	3:1	1.5:1	2:1	3:1
7 ft [2.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
13 ft [4.0 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
20 ft [6.1 m]	2 ft [0.6 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	4 ft [1.2 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									
	7 ft [2.1 m]	500									
		1,000									
		5,000									
		10,000									
		25,000									

	Do Nothing
	Remove deficient system
	Remove deficient system and install 31" tall W-beam guardrail with a crashworthy end treatment